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ORIGINAL ARTICLES.

The Contact Metamorphism and Related Phenomena in the Neighbourhood of Marulan, New South Wales.

Part I: The Quartz-monzonite—Limestone Contact.

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(PLATE XII.)

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Introduction.

THE township of Marulan lies about 100 miles south-west of Sydney, New South Wales. Adjoining is the village of Tallong, and the district surrounding these places is one of great geological interest, because of the variety existing among the sedimentary and eruptive rocks, and also on account of their structural relations. W. G. Woolnough gave a good general account of the geology of this region in 1909,[1] having previously [2] (1906) collaborated with Griffith Taylor in describing the physiography. The area is part of the southern tableland of N.S.W., the general elevation being about 2,000 feet, with residuals rising to a maximum height of 2,350 feet. Highly contorted slates and shattered quartzites of Ordovician age, and tilted Silurian strata which almost certainly are unconformable with the former, are invaded by a plutonic

[1] *Proc. Linn. Soc. N.S.W.*, xxxiv, 1909, 782–808.
[2] *Proc. Linn. Soc. N.S.W.*, xxxi, 1906, 546–54.

complex which is roughly elliptical in plan, with a meridional trend, and possesses a southward prolongation.

This batholith has not yet been fully investigated and the descriptions given by Woolnough refer to the eastern half of the

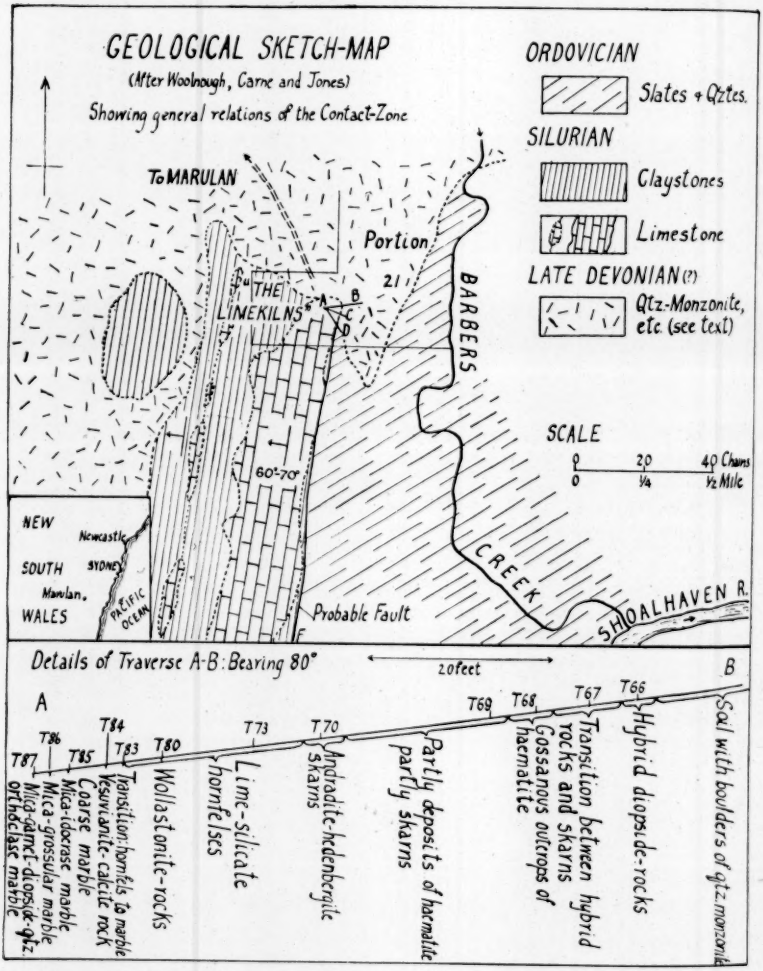


FIG. 1.—Geological sketch-map of the neighbourhood of "The Limekilns", near Marulan, N.S.W.

mass. The main types present comprise hornblende-biotite-granite, quartz-monzonite, granodiorite, quartz-porphyry and quartz-porphyrite. Little is known concerning the relations of these, but it is sufficient to note here that the extensive granodiorite

and quartz-monzonite, and more restricted quartz-porphyrite of the eastern part of the mass, appear to grade into one another and definitely invade the Ordovician and Silurian sediments, but are covered by Permo-Carboniferous rocks. On the criteria of petrological character and tectonic relationships it is very probable that this eruptive mass is of late Devonian age.

About five miles to the south-east of Marulan village is the locality known as "The Limekilns", where the quarries and extensive works of the Southern Portland Cement Co. are situated. In this neighbourhood is to be found the contact between quartz-monzonite and limestone. Here, just on the edge of the plateau, the igneous rock cuts across the strike of the Silurian sediments and has strongly metamorphosed them.

The sediments comprise two belts of limestone separated by claystones and quartzites, the general dip being to the west. The eastern belt is more persistent and much thicker than the western one, and shows the more pronounced metamorphism. It also dips more steeply, and observations [1] made since the writer last visited the area suggest that the structural features are not as simple as shown on Dr. Woolnough's map, which has formed the basis of the map in Fig. 1. In this area the eastern belt seems thrown against the Ordovician by a vertical fault, which runs close to the contact and is older than the quartz-monzonite.

A brief preliminary account of the metamorphic phenomena, accompanied by petrographical notes and some analyses, was given by Dr. Woolnough in the paper cited above, and he anticipated making a more complete investigation. He has, however, definitely relinquished the plan of further examination, and is heartily in accord with the writer carrying out the work.

In the preliminary account Woolnough described a section across the contact-zone and recorded the presence of such minerals as wollastonite, vesuvianite, diopside, and garnet in the calc-silicate rocks. He also referred to some rocks, which, it is clear, were identical with those described in this paper as skarns, and recorded some significant variation in the mineralogical constitution of the intrusive near its margin, hinting at the possibility of assimilation of sedimentary material being the cause of this variation.

Beyond this brief notice, and the quoting of some analyses, the present writer will make no further reference to the petrographical notes given in that paper. He would like, however, to pay a tribute to the splendid pioneering work which Dr. Woolnough, with some senior students, carried out in a very rugged region.

General Field Relations.

The present study has been made almost entirely upon the metamorphism of the eastern belt, since the alteration of the western belt is less extensive and not so well exposed, but it may be mentioned

[1] Communication from Professor W. R. Browne, of Sydney.

that lime-silicates occur in the northern end of this belt. It should be remarked also, that metasomatic action by siliceous waters derived from the intrusion has produced some cherty and quartzitic rocks in this locality and elsewhere in the neighbourhood. In particular, one interesting case is that known locally as the " concertina rock ", a banded rock which has weathered differentially to give a striking appearance. This was first pointed out to the writer by Professor Browne, who has suggested that it is due to the silicification of banded shales such as occur in this area. The possibility that the original sediment was a rhythmically-banded limestone must, however, be recognized.

The massive, lower or eastern limestone reaches its northern limit in Portion 21, Parish of Marulan, County of Argyle, where it is interrupted by the quartz-monzonite (see Fig. 1). Apart from the development of calc-silicate rocks, the limestone has been transformed across the whole width of the outcrop into a fairly coarse marble with saccharoidal texture. The rock is generally dazzling-white when freshly broken, or pale bluish-white, with occasional yellow and brown staining. Away from the contact the limestone has recrystallized without combining with any small amount of silica that may rarely be present. Thus in these places the quartz-calcite association has been stable.

The general purity of the limestone in places beyond the contact-zone, and indeed along the strike of this, is attested by analyses given in Carne [1] and Jones' " Limestone Deposits of N.S.W.", the average percentages from five analyses of samples taken in the neighbourhood of the contact being: $CaCO_3$ 99·14; $MgCO_3$ 0·88; $Fe_2O_3 + Al_2O_3$, 0·16; gangue 0·30. Trenches cut across the belt in the vicinity of the contact, show that the limestone right to within a few feet of the hornfelses is almost pure calcite with a bluish or yellowish colour and with wide variation of texture. The occurrence of impurities, now in the form of silicates, is restricted to fine strings of minerals or isolated crystals.

The contact-zone occurs in Portion 21 on gently sloping ground, and shows characteristic outcrops of hornfelses and skarns. The rocks have weathered to give, in the former case, " clinkery " surfaces, and in the latter a gossanous appearance. In the first case it is due to the variable resistance of the constituent minerals, the calcite and wollastonite having been removed leaving cavities. From the last crystalline limestone which contains no silicate minerals to the first appearance of normal quartz-monzonite is about 110 feet, but at a distance of 80 feet soil derived from the igneous rock occurs, and thus the zone of hornfelses, marbles, and skarns is about 75 feet wide. (Of course, it must always be remembered that the whole of the limestone has been recrystallized, and thus is within the aureole of the quartz-

[1] *Geol. Surv. N.S.W., Mineral Resources,* No. 25, 1919, 354.

monzonite ; but the interest lies in the zone of silicates, and the term " contact-zone " is used in this respect.) The details on Fig. 1 show something of the mode of occurrence of the altered limestones and associated rocks. Series of specimens were collected along three lines of traverse at points frequently one foot apart and sometimes six inches apart. That along B–A (Fig. 1) is the most instructive, and it is seen that the order of rocks from B to A is as follows : quartz-monzonite, hybrid diopside-rocks, hedenbergite-andradite skarns, deposits of haematite passing into skarns, lime-silicate hornfelses, hornfelses with bands of coarse marble, and marbles with phlogopite, grossular, vesuvianite, potash felspar, diopside and free quartz in varying associations, all of which will be treated in detail below.

Along the traverse A–C some coarse marbles occur, these being succeeded towards C by hybrid rocks, which are in turn followed by skarns. On this traverse there are some examples of skarn-lenses in hybrid rocks. The series along A–D consists of marbles followed by hornfelses, some of which contain abundant idioblasts of grossular. The last two traverses end on masses of talus which obscures the relationships.

Petrography.

1. *The quartz-monzonite.*

The quartz-monzonite in the area adjacent to the contact grades into that type described by Woolnough as the Glenrock granodiorite. A brief description of the former phase is as follows :—Fairly dark in colour due to abundant femic minerals, with medium to fine grainsize, felspars, hornblende, biotite and pyrites being distinguishable macroscopically. Under the microscope the following are seen :—Zoned plagioclase, An_{40} to An_{25}, with twinning on the albite, carlsbad, and pericline laws, the central zones being altered to kaolin, sericite, calcite, and a little zoisite (?) ; orthoclase with poor (001) cleavage and incipient kaolinization ; interstitial quartz ; biotite is bent and altering to chlorite, sometimes to intercleavage masses of sericite and also to an appreciable amount of secondary sphene, showing titanium-content. Hornblende is altering to chlorite also. The accessories comprise apatite, pyrites, magnetite with haematite, and zircon. The fabric of the rock is monzonitic, the lime-soda felspars being in stout prisms up to 2 mm. in length, and the orthoclase entirely allotriomorphic. Biotite seems to have crystallized before hornblende, both being subidiomorphic. There is no pyroxene in the normal rock from this locality.

2. *The marbles, hornfelses, skarns, and hybrid diopside-rocks.*

(*a*) *Textural characters.*

The marbles are essentially granulose, the subordinate silicates being xenoblastic with the exception of vesuvianite which forms crystals up to $\frac{1}{3}$ mm. in diameter. The textures of the hornfelses

varies as regards grain, but is essentially of the same type. Glistening-white, cleaved wollastonite crystals and grains of grossular are intimately associated with crystals, plates and irregular masses of vesuvianite with the production of heteroblastic effects. Small amounts of diopside, epidote and sphene are seen only in thin section. The grossular is not so abundant as the other lime-silicates, generally being scattered through the rocks, but in certain places there is strong local development of good crystals in rocks containing little vesuvianite. At times masses of pure wollastonite arise when this mineral is developed in patches and roughly in bands. Residual calcite is found filling intergranular spaces, and increases in quantity to become important in some rudely banded-rocks which originally were limestones with intercalations of clayey strata. In some of these poorly-banded rocks there are alternations of bluish calcite and vesuvianite, much of the latter having altered to a green substance. The marbles succeeding the hornfelses away from the contact possess strings of vesuvianite and grossular and flakes of mica, the last sometimes being the sole silicate visible in hand-specimen.

Under the microscope it is seen that wollastonite is always strongly idioblastic to the rest of the minerals. In most cases it is present in groups of large crystals, but in some rocks the texture suggests that some of the later-formed wollastonite was of fine grain. Cases of this are seen in certain garnet-rich rocks where the smaller wollastonite units have been pushed aside by the growth of the grossular crystals (e.g. T. 108, see Fig. 1, Plate XII). In such rocks the structure is porphyroblastic. In the other hornfelses the presence of large vesuvianite plates enclosing grossular and wollastonite gives rise to beautiful examples of poikiloblastic texture.

The skarns are dense rocks of a dark, brownish-green colour with resinous lustre, the brownish andradite being conspicuous. Under the microscope the garnet and associated hedenbergite show splendid diablastic intergrowths (see Fig. 5, Plate XII), the occasional calcite and finely-divided quartz tending to give heteroblastic structure.

The hybrid diopside-rocks are dark in colour, stumpy pyroxene crystals showing up against a greyish-green ground. Under the microscope one sees the idiomorphic and subidiomorphic diopside and sphene contrasted with the allotriomorphic orthoclase, quartz, prehnite and clinozoisite, and pseudomorphs of chlorite and sericite indicate the former existence of idiomorphic prisms of plagioclase (see Fig. 6, Plate XII). It is clear that the texture of the rocks before magmatic alteration was monzonitic and similar to that of the normal rock.

(*b*) *Mineral Descriptions.*

We now proceed to the description of the minerals constituting the marbles, hornfelses and related skarns and hybrid rocks. The

refractive indices were determined approximately with immersion-liquids using sodium-light.

Wollastonite.

This mineral is one of the most characteristic in the hornfelses, being developed in glistening-white, cleaved crystals up to 5mm. in length. The habit is inclined to be tabular parallel to *a* (100), but more frequently prismatic parallel to the b-axis, with approximately equidimensional cross-sections. The forms seen in thin sections are *a* (100), *c* (001), *t* (101), *v* ($\bar{1}01$) and *o* ($\bar{1}02$), terminal faces in the *a*–*b* zone being apparently of rare occurrence. The cleavage is very noticeable in hand-specimen, and in section one sees the (100) and (001) cleavages well developed, the former being the stronger. Poor cleavage parallel to ($\bar{1}01$) is also present and a further occurrence is that of a fairly good cleavage parallel to (101). This cleavage is not mentioned in text-books, except in the recent one of Winchell, where it is shown in a figure, but is not specifically recorded in the text. In the present case the angles between this (101) cleavage and those parallel to (001) and (100) are 40° and 44½° respectively (see Fig. 4 (*a*), Plate XII).

Twinning on (100) is occasionally developed, giving simple and polysynthetic effects. In particular, T. 72 shows multiple twinning in a (010) section, the (001) cleavages in the compounded individuals lying at angles of 168° with one another.

Cross-sections of wollastonite are distinguished from similarly appearing diopside sections by the fact that the extinction in wollastonite is given by $X \wedge c = 32°$. The maximum D.R. is ·015 in (010) sections, and in these one sees a peculiar patchy extinction. The axial plane is always parallel to (010), across the elongation, and the optic axial angle is small, as evidenced by the curvature and spacing of the isogyres in sections perpendicular to X. The mineral is constantly negative with slight inclined dispersion, $\rho > v$. The R.I.[1] was found to range from $\alpha' = 1{\cdot}618$ to $\gamma' = 1{\cdot}632$, and the Sp. Gr. determined at $D^{1.5}_{4} = 2{\cdot}841$.

Wollastonite is generally quite stable, but in certain rocks it is passing peripherally and also along the cleavage-cracks into finely divided calcite, which eventually may replace quite a considerable portion of the grain. In most of these examples there is no secondary silica visible, but this does occur in T. 100 and T. 103. In other slides opal has been noticed in tiny patches not in close connection with the secondary calcite. This change to calcite and silica is not considered as retrogressive metamorphism, as it is always seen in rocks which have suffered weathering.

Another decomposition product, whose identity the writer has not been able to establish, is developed in fine scales along the cleavages, and has medium refraction and high bifringence.

[1] α' and γ' refer respectively to the least and greatest indices determined approximately by the Schroeder-Becke Immersion method.

Vesuvianite.

This is one of the most important contact minerals. It occurs either in crystals up to 4 mm. diameter, or in large granular masses and plates. The crystals are brittle and difficult to remove from the rock, and accurate angular measurements have not been possible, but the presence of *a* (100), *m* (110), and *p* (111) faces was noted, the habit generally being stout-bipyramidal. The colour is dark brown, rarely paler brown, and the lustre vitreous.

In thin section many interesting features are apparent. The development of the faces mentioned above and the infrequent occurrence of *c* (001) are responsible for the prevalence of almost equidimensional six-sided sections. Most of the plates and massive portions seem to be homogeneous until examined in convergent light, when they show they are made up of many crystal-units which are aggregated together, partly in parallel-growth, with very rarely any intercrystal spaces. The boundaries of the plates are often re-entrant due to associated crystal margins. The plates not exhibiting this aggregate-structure frequently show a poor cleavage of indetermine orientation.

The separate crystals and those constituting the plates show beautiful zonary banding under crossed Nicols (T. 73). Where zoning is absent, a less regular arrangement of areas differing in birefringence is always seen, and sometimes a peculiar patchy extinction similar to that described by Eckermann [1] for the vesuvianite of the Mansjö Mountain contact is observed. The zonal scheme may be of three types. First, the central portion may be relatively broad, followed by narrow bands to the periphery, all zones showing varying shades of the same general interference colour. Secondly, the kernel may be somewhat irregular and possess an interference colour distinctly different from that of the peripheral bands. Again, the centre may be broad and similar to the rest of the zones with the exception of the peneperipheral layer, which may consist of a series of "clots" arranged concentrically with the rest of the crystal and possessing a separate colour. As many as eight zones have been noted in one crystal (see Fig. 4 (*b*), Plate XII).

The interference colours of the mineral are nearly always strikingly abnormal. In sections about ·056 mm. thick the mineral shows strong Prussian blue and a peculiar turbid yellowish brown. In thinner sections, ·035 — ·04 mm., the principal colours are dull brownish-yellow and brownish-green for some parts, and violet for others. In a few cases almost pure white is associated with the blue. On account of the low, variable birefringence one sees pronounced changes when the stage is rotated, the mineral failing to extinguish completely.

[1] H. von Eckermann, *The Rocks and Contact Minerals of the Mansjö Mountain*, Stockholm, 1922, 373.

The sign of the vesuvianite has been found to vary with the different zones, the blue portions being positive and the yellowish-brown areas negative for sections ranging from ·035 to ·05 mm. For sections of other thickness it would doubtless be found that variations in the colour scheme and its relation to the sign would result. Some sectors are absolutely isotropic and the mineral is apparently not anomalously biaxial. Many of the characters described agree with those recorded by Goldschmidt [1] for the vesuvianite of the Kristiania contact and by Munteanu-Murgoci [2] for the mineral of the Paringu-Massif.

The mineral is pleochroic in thick sections giving, O = pale greyish green, and E = pale wine-red, E > O. The R.I. has been found to lie within the limits 1·724 and 1·730, and the Sp. Gr. has been determined at $D\ {}^{15}_{4} = 3{\cdot}360$. Contrasted with the bulk of the occurrences is the vesuvianite occurring in T. 108. Here the crystals which are pale pinkish and pleochroic, show normal low greys of the first order, and the sign and elongation are negative.

The decomposition of vesuvianite presents some very interesting features. On account of some isomorphous replacement of the fundamental bases having occurred, a variety of alteration products has developed. The details observed may be recorded fully, because vesuvianite is generally described in literature as being rarely altered. In the Marulan rocks the chief products give rise to the following assemblages :—prehnite-calcite-grossular-silica, prehnite-epidote-calcite, calcite and brownish-stained kaolin, and lastly a fibrous mineral together with prehnite, calcite and grossular. The epidote develops from the more highly coloured variety of vesuvianite, and no doubt the grossular sometimes contains a little iron.

The change to prehnite-grossular-calcite-silica, which is very frequent, may be suggested by the following ideal reactions :—

$$\underset{\substack{\text{vesuvianite}\\(\text{Rosenbusch-}\\\text{Mügge})}}{4HCa_2Al(SiO_4)_2} + 3CO_2 = \underset{\text{prehnite}}{H_2Ca_2Al_2(SiO_4)_3} + \underset{\text{grossular}}{Ca_3Al_2(SiO_4)_3} + 3CaCO_3 + 2SiO_2 + H_2O.$$

$$\underset{\substack{\text{vesuvianite}\\(\text{Iddings})}}{2HCa_6Al_3Si_5O_{21}} + 5CO_2 + H_2O = 2H_2Ca_2Al_2(SiO_4)_3 + Ca_3Al_2(SiO_4)_3 + 5CaCO_3 + SiO_2$$

Sometimes the silica is not found in close connection with the other products, but rather as small masses of finely divided material elsewhere in the slide.

In the equations for vesuvianite, alternative formulae are given for this mineral, since various workers have ascribed varying compositions to it. The first given above was used by Goldschmidt for the Kristiania rocks, and adopted as recently as 1925 by Mügge

[1] *Vid. Selsk. Skrifter*, 1911, No. 1, 439–44.
[2] *Bull. de la Soc. des Sciences*, Bukarest, ix, 1900, 61.

in his edition of Rosenbusch's text-book.[1] The second was given in Iddings' text-book (1911), and was also arrived at by Eckermann [2] after exhaustive examination of chemical data concerning certain Swedish vesuvianites. He concluded that vesuvianite may be of two types, consisting of alternative groups of molecules, one group being, in its simplest form, identical with the formula given by Iddings.

The fibrous alteration product may now be described. It may be seen developing in patches over the vesuvianite and some areas 2 mm. across have been seen, from which the mineral has been isolated and tested. The mineral is apparently almost colourless, but often greyish, due to innumerable fine inclusions. The fibrous character is strongly developed and there is cleavage parallel to the fibres, against which extinction is parallel. This is the direction of the axial plane, 2V being small. Optical tests suggest that the mineral, which is always biaxial positive, is orthorhombic. The D.R. is low, being about ·0035, and the R.Is. lie between 1·705 and 1·714. The elongation is nearly always negative, but some sections which are more finely fibrous than the average show positive elongation. Dr. Tilley pointed out to the writer that, apart from the refraction, this mineral appeared comparable with the hydrated calcium-aluminium-silicates, riversideite and foshagite, which occur associated with vesuvianite and have been described by Eakle.[3] A micro-chemical test was then carried out, concentrated HCl causing slight alteration of the periphery of the mineral, the fibrous character disappearing and the mineral becoming isotropic, while weaker acid had no effect. These results rule out the possibility of the mineral being related to the hydrous silicates mentioned above, and it is hoped that it will be possible at a later date to obtain sufficient material for an analysis.

Diopside.

Diopside occurs sparingly in the altered limestones, but it is abundant in certain rocks which are interpreted below as contaminated igneous rocks. In the former the mineral characters are close to those of pure diopside. In the latter, while diopside is abundant the composition is sometimes close to that of aluminous augite, judging by the double refraction and extinction values.

In the calc-silicate rocks the mineral is almost always completely xenoblastic with poorly developed cleavage. The maximum extinction $Z \wedge c$ in varieties from different parts of the contract zone ranges from 38–43°, and the double refraction is ·027. The R.I. was found to range from $\alpha' = 1{\cdot}699$ to $\gamma' = 1{\cdot}725$.

In the hybrid rocks the diopside is abundant in well formed

[1] *Mikroscopische Physiographie*, 5th Edition, Stuttgart, 1925, 132.
[2] *Geol. Fören. Förh. Stockholm*, Nov.–Dec., 1923, 497–8.
[3] *Bull. Dep't. Geol. Univ. California*, 1917, 327. *Amer. Min.*, x, 1925, 97.

crystals, the bulk of which are colourless. The habit is stout-prismatic and the (110) cleavage is well shown, with also a fairly good development of cleavage parallel to (100). Twinning is not so common, being single rather than multiple, and always on (100). The extinction $Z \wedge c$ for the lime-diopside has a maximum value of 42°. In cases where apparently there is a decided aluminous content the maximum angle is 53°. These differences in extinction are correlated with variations in maximum interference tints, those of diopside corresponding to a birefringence of about ·028, and in the case of augite about ·022.

The pyroxene is very fresh on the whole, the only slight alteration being to greenish amphibole.

Hedenbergite.

Besides pyroxene definitely referable to diopside rich in lime, there is developed exclusively in the skarns, a pale to fairly bright green pyroxene which may be called hedenbergite, provided the name is not taken to imply pure lime-iron-metasilicate, but a mineral in which the ratio of hedenbergite to diopside molecules is very high.

This pyroxene is generally quite xenoblastic and often intergrown with andradite, its chief associate. The colour is characteristic, the pigmentation sometimes being patchy, and the absorption scheme is as follows:—

X = palest greyish green.
Y = greyish green.
Z = fairly strong bluish green, $Z > > Y > X$.

The (110) cleavage is well developed in certain rocks, but never as well as in the diopsides. Twinning on (100) has been observed only once or twice. The D.R. is distinctly lower than that of diopside, the maximum being ·022, this value doubtless reflecting the presence of some diopside in solid solution. The extinction $Z \wedge c$ was found in a number of rocks to be less than that for pure hedenbergite, the value obtained ranging from 42–44° but in certain cases (e.g. T. 100), the maximum of 48° was obtained. The birefringence is always positive, and the interference figures indicate an axial angle of medium value and slight dispersion, $\rho > v$.

The R.Is. were found to range from $\alpha' = 1{\cdot}720$ and $\gamma' = 1{\cdot}736$, to $\alpha' = 1{\cdot}722$ and $y' = 1{\cdot}739$, this representing approximately a composition-interval from $He_{67}Di_{33}$ to $He_{73}Di_{27}$.

The hedenbergite is mostly unaltered, but in certain cases, (T. 70, T. 99) there is a change to pleochroic fibrous actinolite, the incidence of amphibolization being related to cracks through the rock, in which secondary magnetie-dust and haematite stains occur. This alteration again is to be correlated with the magnesia-content in the pyroxene, and in the particular rocks cited, is in accord with the composition indicated by the values of the refraction.

Grossular.

This variety of garnet is absent from the skarns but is fairly well-developed in the hornfelses. In hand-specimen the mineral is either fawn or light-brown in colour with a vitreous lustre and sub-conchoidal fracture. The grains are generally very small, but in one part of the contact-zone, good crystals up to 3 mm. diameter are embedded in wollastonite and calcite, e.g. T. 108.

The thin slices show the general absence of good crystal-form, some suggestion of dodecahedra and trapezohedra being noticed in a few cases, but the general form being xenoblastic with no sign of cleavage. As an exception, in T. 108 splendid idioblasts are seen, the sections indicating simple tabular crystals with dodecahedra almost exclusively present. Some very small crystals of grossular occur in such a way that it is difficult to decide whether they are due to recrystallization or alteration of vesuvianite.

The irregular growths are generally isotropic, while the well-formed crystals show anomalous birefringence with characteristic zonal and partitionate structures. This distinction has been noted by various workers, and it would appear that the better the development of the crystal, the more prone is it to undergo structural re-arrangement.

The R.I. has been found to lie within the limits 1·749 and 1·753 and the density was determined at $D^{17}_4 = 3{\cdot}689$. These data, when interpreted according to the results of Ford's [1] studies, indicate that the garnet is a fairly pure grossular.

The grossular is usually unaltered, but in one rock, T. 108, secondary scapolite and calcite have developed in cracks.

Andradite.

Andradite garnet has been found only in the skarns, where it occurs with a deep brown colour, resinous lustre and a clean fracture. The chief criteria aiding its identification are the R.I. which was found to be much higher than a liquid of value 1·805, $\pm$ ·005, and the density which was determined at $D^{18}_4 = 3{\cdot}82$.

The mode of occurrence is characteristic, the mineral being always completely xenoblastic and genetically associated with hedenbergite. Exceptionally the larger plates, though not idioblastic, give some suggestion of being built up of crystal-units (T. 99) in a manner analogous to that described for vesuvianite.

The general colour in thin section is pale pink, rarely colourless. Anomalous twinning and interference colours are seen in some rocks (e.g. T. 68). The andradite is notably fresh, the only case of change being to an indeterminate greenish material which is found in cracks.

[1] *Amer. Journ. Sci.*, xl, 1915, 33.

Calcite.

The almost pure marbles vary in texture and thus calcite is found in both large and small grains and cleavage blocks, the colour also being variable—pearly white, colourless, yellowish and bluish, the last being very characteristic of some of the bands near the contact zone. It is possible that the bluish colour is due to ultra-microscopic inclusions. The finer-grained rocks from near the contact have been studied because of the presence of a small quantity of recrystallized silicates.

The grains of calcite are up to 2 mm. in diameter and show many dustlike impurities. Cleavage, although invariably shown in hand-specimen, is not well displayed in thin section. The twinning is almost entirely parallel to $(01\bar{1}2)$, the lamellae often being broad and bisecting the acute angle of the cleavage-rhombs—a criterion in favour of calcite as opposed to dolomite, as pointed out by Tilley.[1] Some of the twinning has probably been produced by pressure, which is evidenced by bent cleavage-cracks and curved twin-lamellae, the development of local twinning being seen in areas showing pressure effects. Inclusions of iron-ore have been haematitized with resultant staining along cracks. Tests with staining re-agents have shown the complete absence of dolomite from the marbles.

Sphene.

In the contaminated igneous rocks occurring right at the contact, sphene becomes an important constituent, and it is sparingly present in one or two of the hornfelses. It may occur in separate crystals, in parallel growths, or in very irregular grains. At times tiny granules form characteristic segregations, while the maximum grainsize is $\frac{3}{4}$ mm. The faces *m* (110) and *n* (111) are common and *a* (100) is less frequent, and the parallel grouping gives rise to distinctive multipyramidal terminations, which show serrated edges in section. When not diamond-shaped the single crystals are generally elongated parallal to *m* (110). Cleavage parallel to (110) is perfectly developed in a few sections (T. 98 and T. 94) and the maximum extinction angle measured against this cleavage was large, but the orientation of the section was not determinable.

Pleochroism is quite noticeable with

X = pale yellowish tint.
Y = pale greenish yellow.
Z = pinkish brown, $Z > > Y = X$.

The high dispersion is evidenced by the failure of the mineral to extinguish completely, and the interference figures bespeak a small optic axial angle. The sign of the mineral is positive. An interesting feature in many of the hybrid rocks (T. 101 and T. 102)

[1] Geol. Mag., LVII, 1920, 453.

is the presence in the sphene of nuclear clots of ilmenitic iron ore (as shown by leucoxenization). The significance of this is dealt with below.

Prehnite.

Prehnite as a primary mineral is particularly abundant in some of the diopside-rocks. It occurs in ragged aggregates in most cases, although occasionally approaching subidiomorphism. In a few special cases it produces with quartz some beautiful intergrowths. The R.I. has been tested with liquids and found to lie between 1·610 and 1·638, but in most cases to be between 1·624 and 1·635. The D.R. varies widely in differing sections, often being very low, the maximum being ·028. Cleavage, apparently parallel to (001) is well developed, and against this the extinction is straight. There is frequently a radial growth giving characteristic extinction-effects. Sections across the cleavage, particularly those parallel to the axial plane, show a peculiar structure under crossed Nicols, whereby the mineral is divided into segments of slightly varying orientation, which are sometimes alternate in arrangement. As the stage is rotated the extinction-effect is distinctive, almost suggesting twinning, but the structure is probably related to the irregular growth of the aggregates.

The better developed individuals show negative elongation, the habit tending to be tabular parallel to (100). Occasionally veinlets of the prehnite cut across some of the hybrid rocks.

Phlogopite.

This mineral is often pale green to colourless, at other times pale greenish-brown. The pleochroism is weak and fits into the following schemes, according to the variety :—

(i) X = colourless, Y = pale sea-green = Z ; Z = Y > X.

(ii) X = colourless, Y = pale brown, Z = greenish brown ; Z > Y > X.

The composition varies and it is clear that the brown variety is the more ferriferous, on account of its discharge of iron-oxide. The greenish variety alters to pale-coloured chlorite. The flakes are generally small, the maximum being $\frac{3}{2}$ mm. in length, all of which are bent. Sections of low birefringence, and almost perpendicular to the X-axis, give a pseudo-uniaxial figure, which is indicative of a very small axial angle.

Scapolite.

A very subordinate amount of scapolite occurs in some rocks, but there is doubt as to whether the mineral has developed with the primary metamorphism. Thus in most cases the scapolite has come from alteration of grossular, although some small distinct patches occur in a hornfels and in a marble from the western belt. The variety developed is fairly strongly calcic, the maximum D.R. being about ·031. Cleavage parallel to (100) is poorly shown, while only a faint trace of prismatic cleavage is seen.

Potash Felspar.

Large plates of orthoclase formerly present in the hybrid rocks have been kaolinized and otherwise altered. Some sections suggested microcline, but no definite diagnosis was possible.

In the marbles the potash felspar is very subordinate, having grown around tiny grossular crystals and flakes of mica. Its precise nature is indeterminate, but one sees the imperfect basal cleavage and slight kaolinization, the mineral being quite xenoblastic.

Clinozoisite-Epidote.

Quite appreciable amounts of this occur in the hybrid rocks, the material occupying intergranular spaces and showing almost colourless character. The (001) cleavage is well developed, the extinction against this being at high angles in clinopinacoidal sections. The anomalous interference colours are very distinctive, these being mainly blues which grade into normal second order colours in parts of the grains where the epidote component is present. There is an absence, however, of zonal growth, the divisions of the grain being irregular. The areas giving anomalous blue are positive and the epidote-portions negative. Some sections showing parallel extinction on the cleavage suggest zoisite, but no definite diagnosis of this mineral was made.

Other Minerals, including Minor Accessories.

The plagioclase of the hybrid-rocks is much altered, but in one or two remaining sectors one can see that it is less strongly zoned than that of the normal rock, and has a slightly more basic composition, viz., An_{44}. Sercitic mica is abundant in these rocks, having been developed at the expense of both the orthoclase and plagioclase. It may occur in radiating aggregates, sheaves, or in compact masses of flakes. Chlorite, pale green to colourless is often prominent and associated with clinozoisite, sericite and kaolin, while in one rock a little scapolite was found along with other products of alteration of plagioclase.

As minor accessories in the hornfelses there are apatite, zircon and a small amount of iron-ore, often haematitized. Apatite is also well distributed through the diopside-rocks. Quartz is seen in the marbles as clear grains with sharp extinction, and although sometimes scantily developed in the hybrid rocks, is generally absent from these.

Paragenesis and Discussion.

The contact-rocks, whose petrography and general relations have been considered above, may be divided into groups, as follows :—

(*a*) Marbles with small amounts of phlogopite, quartz or scapolite.
(*b*) Phlogopite-grossular marbles.

(*c*) Phlogopite-grossular-orthoclase-diopside-quartz-marbles.
(*d*) Vesuvianite-phlogopite marbles.
(*e*) Lime-silicate hornfelses, with grossular, vesuvianite, diopside, epidote, wollastonite, (scapolite), and residual calcite.
(*f*) Pure wollastonite-rocks.
(*g*) Andradite-hedenbergite skarns, sometimes showing calcite and quartz, and rarely wollastonite, and passing into iron-oxide deposits.

Although the zone of silicate-rocks is not very wide, and the variety among the minerals not very great, there are certain interesting paragenetic features. Wollastonite is found in the inner part of the contact and is absent from silicate-marbles further away from the contact where the quartz-calcite association has been stable. Vesuvianite has a wider range throughout the zone, and occurs in rocks which both contain, and are free from, mica. The last named has not been noticed in wollastonite-vesuvianite assemblages. Grossular seems to have a similar range to vesuvianite and the conditions controlling the appearance of one, in preference to the other, are not known. Possibly the amount of free water in the sediments has some relation to the details of their genesis. Of interest is the association of vesuvianite and epidote, a paragenesis considered unstable by Eckermann.[1] In the hornfelses the most general crystalloblastic order is wollastonite, grossular, vesuvianite, epidote, diopside; while in the marbles phlogopite comes before both orthoclase and vesuvianite, the position of grossular in the order of these rocks being difficult to determine.

Concerning the skarns, it is only necessary here to stress the fact that the andradite and hedenbergite of these rocks are not found with grossular and diopside. The somewhat special association of wollastonite and the minerals of the skarns is considered below.

The consideration of the genesis of the minerals and their modes of assemblage brings us to the question of the origin of the material which, by union with lime, has produced the silicates; because the varying associations will depend on the composition of the sediments and the intensity of the metamorphism to which they have been subjected. In the present case—one of contact metamorphism—the latter will be affected mainly by temperature. Concerning the composition, it is necessary to deal with two main possibilities; either (*a*) there has been considerable addition of magmatic material to pure limestone, or (*b*) impurities in the limestone, and the calcite of the latter have, by molecular re-arrangement and concomitant expulsion of CO_2, given rise to the silicate minerals.

The high degree of purity shown by the limestones in the neighbourhood of, and even to within a few yards of the igneous contact, prompts the thought that an additive metamorphism might have

[1] *Geol. Fören. Stockholm Förhand.*, 1923, Nov.–Dec., 501.

been responsible for the hornfelses. Such addition of magmatic constituents has been advocated by various investigators [1,2,3] who have studied contacts between limestone and intrusives. In particular it is pertinent here to note that the Marulan contact and that at Concepción del Oro (Mexico) have certain features in common. In dealing with the latter Bergeat remarks upon the purity of the limestones in most cases, and uses this fact as negative evidence in favour of addition of magmatic material in the production of the silicates. Some workers have assumed quite readily that considerable quantities of alumina and magnesia, as well as other constituents, may be transferred long distances from the igneous rock. Now it is clear that when the main bulk of a plutonic mass has crystallized and the pneumatolytic stage reached that gaseous constituents may carry out important changes in the minerals of the contact zone, but this will be a metamorphism superimposed upon the earlier thermal change which obtained in the sediments at the time of, and comparatively shortly after the intrusion. Further at a later stage—the hydatogenetic stage—metasomatic changes may be wrought in the rocks contiguous with the margin of the igneous mass. It must be remembered in dealing with the present, or any analogous case, that lowering of temperature in the magma follows its intrusion, with resulting crystallization, which is characterized by endothermic reactions. Thus conditions following the intrusion will be unfavourable for the maintenance of high temperatures in the contiguous sediments.

In the present case the contact-mineral indicating highest temperature-of-formation is wollastonite, which occurs close to the igneous border. Had the silica of this mineral been derived from the magma it would need to have been available when the sediments at the contact were at, or above, the transformation-temperature for the generation of wollastonite. Now from the data to hand concerning the conditions during the crystallization of a magma such as the Marulan quartz-monzonite, one is justified in assuming that silica for the silication of limestone would not be available until a late stage in the cooling-history of the magma, when, it is fairly safe to conclude, the conditions obtaining in the aureole would not favour the crystallization of wollastonite. In a slightly lesser degree the same reasoning applies to the vesuvianite and grossular and certain of the other silicates.

The transfer of magma-constituents can only be effected by passage of gaseous compounds in cracks and pore-spaces, or by watery solutions derived from the intrusive. In the present aureole there is a distinct absence of typical pneumatolytic minerals such as axinite, tourmaline or cassiterite as members of the hornfelses, the only mineral suggesting a wholly pneumatolytic origin being

[1] A. Bergeat, *Neues Jahrbuch*, Beil. Band. xxviii, 1909, 421–572.
[2] H. von Eckermann, loc. cit.
[3] P. Eskola, *Bull. Comm. Geol. Finland*, 1914, No. 40, 253, 252–6.

datolite (?) which occurs in a vein. Even vein-quartz is absent from the hornfelses.

Of course, it must be emphasized that the foregoing remarks do not apply to the skarns, and apart from these it is considered that the only evidence of transfer of magmatic material to the hornfelses is that of the fluorine, which probably, almost certainly, exists in the vesuvianite and phlogopite. Analyses of these minerals, when they occur at contacts, generally show fluorine-content, and the writer considers that in respect of these two minerals *only*, must one postulate an accession of magmatic elements at the Marulan contact, these being strictly limited to compounds of fluorine, and water. Such pneumatolytic action affected the mica and vesuvianite which had developed by normal thermal metamorphism. Apparently these two minerals have affinity with fluorine when such is supplied under pneumatolytic conditions.

Thus the view is here taken that the contact rocks at Marulan arose out of metamorphism which developed at the base of the limestone, where this was impure through the existence of transitional strata such as claystones or shale. Such calcareous shales, interbedded with lenses of fairly pure limestone would be expected at the base of a thick limestone belt, and although not well developed in the " Limekilns " neighbourhood (except at the contact) are present in some amount near the base of the same limestone some distance to the south, at the Bungonia Lookdown.

In some of the hornfelses there is a certain amount of banding visible, due to alternation of calcite and streaks of silicates, and lenses of coarse, pure marbles can just be traced through the inner aureole on the A–C and A–D traverses, although the prevalence of soil makes interpretation difficult. One notices also, that as one proceeds upward stratigraphically, the silicate-content decreases—this being a reflection of a lithological change which one would expect in a thick limestone bed.

Later than the primary metamorphism, and the minor supervening pneumatolytic change, came the metasomatic replacement of recrystallized limestone to give skarns, and about this time were deposited some masses of iron-ore.

Brief Chemical Considerations.

Assuming the marbles and hornfelses to have originated as outlined above, it is clear that the mineral to appear from a sediment of a certain composition will depend on the physical conditions operating. The ideal series to test the various assemblages to appear in an aureole of calcareous sediments, under varying physical controls, would be that in which the composition was constant. It is to be noted that such uniformity of composition is not likely to be attained in calcareous sediments.

Dealing now with the various minerals, it is clear that wollastonite has developed from calcite and silica, according to the simple

well-known reaction. The pure wollastonite-rocks were evidently derived from gritty layers in the limestone. From an analysis given by Woolnough in the paper cited above, there is evidence that some alumina entered into the constitution of this mineral (see Table).

Eskola [1] has suggested that on account of the effect of the release of CO_2, the temperature-of-formation of wollastonite may be lower than that on the Goldschmidt "equilibrium-curve" corresponding to a particular pressure. While there is nothing available to contribute to such a question, it is quite definite that the mineral assemblages containing wollastonite have been stable with falling temperature, no retrogressive metamorphism having occurred. There is no sign, for example, of the development of vesuvianite at the combined expense of wollastonite and grossular.

Boydell,[2] in a recent paper, in discussing the influence of silica upon the dissociation of calcium carbonate under pressure, and the genetic relations of silication and recrystallization of limestones, suggests that $CaCO_3$ and SiO_2 can, in the presence of CO_2, which cannot escape, be non-reacting at a temperature, at which, in the absence of CO_2, wollastonite would develop. In the Marulan contact the quartz-calcite association is present in rocks containing the low-temperature mineral, phlogopite, which rocks occur in the outer part of the silicate-zone where the temperature apparently has not been sufficiently high for the formation of the metasilicate. Thus minerals expressive of low-grade thermal metamorphism, such as phlogopite, or (in the case of dolomitic limestones), tremolite, if occurring with a calcite-quartz paragenesis, may be used as criteria to indicate that the quartz-calcite stability was not due to an inhibited decomposition of calcium carbonate, at high temperatures, consequent upon the inability of CO_2 to escape.

In the following consideration of the formation of the other silicates, certain ideal equations are given as suggesting possible reactions, and particularly with a view of strengthening the hypothesis that impurities such as do occur in calcareous rocks could provide the material for the silicates observed. It should be understood that it is probable more complex reactions of an intermediate character have ensued, and that catalysts, such as water, have performed important functions. In most of the cases considered, definite formulae for the significant minerals have not been given, although all of the equations have been tested by employing the simplest theoretical formulae, which have been assigned in recent times to the various minerals. With regard to the use of dolomite as a reaction-unit, it is necessary to state that while no excess of this occurs in the marbles, the very small amount of magnesia in the analyses of some of the rocks, may

[1] *Journ. Geol.*, xxx, 1922, 281–2.
[2] *Trans. Inst. Min. Met.*, xxxvii, 1928, 66–7.

just possibly represent the former existence of slight dolomitization. Alternatively, as assumed in certain cases below, the magnesia may quite reasonably have been present as a finely divided chloritic constituent.

Taking the minerals grossular and vesuvianite it is seen that these are in intimate association, the latter generally forming later. In one slide it appears as if some of the vesuvianite has been made from grossular during the advance of the metamorphism. These minerals may be developed from quartz, calcite and kaolin, the reactions being expressed by simple equations which need no statement here. In connection with the vesuvianite, it is fairly clear that a little magnesia, iron and fluorine have entered into its constitution, the first two ingredients being developed from detrital material and replacing calcium in the molecule. Similarly in the case of grossular a little isomorphous replacement by andradite molecules has doubtless occurred.

Epidote is sometimes found with vesuvianite. It will develop from kaolin, calcite and iron-oxide, possibly at a temperature slightly lower than that for vesuvianite and grossular. The following suggested scheme shows the development of iron-free epidote. The entry of iron into the reaction, by replacing some aluminium in the clino-zoisite molecule would give common epidote.

$$\underset{\text{kaolin}}{3H_4Al_2Si_2O_9} + \underset{\text{calcite}}{4CaCO_3} = \underset{\text{epidote}}{2HCa_2Al_3Si_3O_{13}} + 4CO_2 + 5H_2O$$

Diopside is very sparingly present in the hornfelses, and may have obtained its magnesia from dolomite or chlorite. In some of the marbles in the lower grades of the contact-zone this pyroxene is associated with phlogopite, orthoclase, grossular, and free quartz. Assuming magnesia to be contained in chlorite, and detrital sericite to be present, the reaction may be as indicated below, if the chlorite be regarded as a simple mixture of the serpentine and amesite molecules :—

$$\underset{\text{(Sp. + At)}}{\text{chlorite}} + 2\ \text{sericite} + 11\ \text{calcite} + 10\ \text{quartz} = \text{phlogopite} + 3\ \underset{\text{orthoclase}}{\text{grossular}} + 2\ \text{diopside} + 11CO_2 + 5H_2O$$

An excess of quartz can be provided for by addition to both sides of the equation.

The phlogopite-grossular marbles, which contain very little of these silicates, may be indicated by the succeeding reaction :—

$$\text{sericite} + 3\ \text{dolomite} + 3\ \text{quartz} = \text{phlogopite} + \text{grossular} + 6CO_2$$

Some marbles contain a very small amount of mica and appreciable amounts of vesuvianite (see Fig. 2, Plate XII). The assumption of some dolomite being present allows for the following reaction :—

$$\text{sericite} + 3\ \text{dolomite} + \text{calcite} + 4\ \text{quartz} + H_2O = \text{phlogopite} + 2\ \text{vesuvianite}$$

or, in the absence of dolomitic material, the genesis may be related

to the following scheme, the detrital chlorite being regarded as close in composition to the serpentine end of the series :—

$$\text{sericite} + \underset{\text{(Sp.)}}{\text{chlorite}} = \text{mica} + \text{vesuvianite} + H_2O + CO_2$$

The scapolite which has not formed at the expense of grossular may have been generated as a result of the action of chlorine which may have been present in NaCl disseminated through the sediments. There is little to support the view that magmatic chlorine has been responsible.

Sphene, a minor accessory in very few hornfelses, has doubtless formed according to the generally accepted chemical scheme, and apatite, which is only sparingly developed, may be regenerated detrital material, or residual crystals which have persisted throughout the metamorphism. The last statement also refers to a stray crystal of zircon, which was seen in one of the hornfelses.

	A.	B.	C.
SiO_2	44·82	39·49	50·71
Al_2O_3	5·94	15·97	2·07
Fe_2O_3	3·17	7·09	0·69
FeO	1·26	2·59	—
MgO	1·31	1·97	0·07
CaO	41·21	31·60	46·53
Na_2O	0·26	0·12	—
K_2O	0·06	abs.	—
H_2O+	0·26	0·13	—
H_2O-	0·14	0·04	—
TiO_2	0·41	1·01	—
CO_2	—	0·17	—
MnO	0·13	0·32	—
	98·97	100·50	100·07

A. Wollastonite–vesuvianite–grossular hornfels; "The Limekilns," near Marulan, Anal. W. R. Browne.
B. Garnet–pyroxene rock (skarn); same locality. Anal. A. B. Walkom.
C. Wollastonite; same locality. Anal. A. B. Walkom.
(These analyses are given in the paper by W. G. Woolnough.)

In the table above some analyses given in Dr. Woolnough's paper are quoted. The first, which is of one of the hornfelses, shows that the specimen analysed was rich in wollastonite, vesuvianite and grossular being subordinate. The iron present was, no doubt, distributed between vesuvianite and the andradite molecule of the garnet. The small amount of magnesia present may have been present in diopside or in the vesuvianite, and this low value is in keeping with the small quantity of magnesia in the marbles which have been analysed (see above).

The second analysis is of a rock, whose description in Woolnough's paper leads one to conclude that it was a skarn-type. The figure for alumina shows that there was some grossular isomorphously replacing the andradite, while the magnesia, which is again low, shows that the pyroxene was strongly hedenbergitic.

Development of the Skarns.

The term skarn has been used here in the fairly wide sense, originally employed by Goldschmidt,[1] Eskola [2] and others—thus embracing silicate-rocks produced by the metasomatism of limestone. The general relations and mineralogical constitution of these rocks have been given above, it having been shown that they are made up almost entirely of brown andradite-garnet and green hedenbergite, the minor constituents being silica and calcite, and in one specimen, T. 100, some wollastonite. They are associated with masses of haematite and a little magnetite which have been deposited in cracks along the contact, and perhaps in some places have replaced limestone.

The genesis of these rocks is certainly distinct from that of the normal lime-silicate hornfelses and marbles. Thus veins of quartz are seen threading through the skarns, and under the microscope there is clear indication of the manner in which limestone has been replaced by silica and iron. Numerous strings of andradite are found ramifying through and replacing the calcite, and in amongst the intimately associated garnet and calcite there is finely divided quartz which has been deposited from solution, because it is sometimes seen to be related to the presence of vein-quartz in the rock. At times this silica appears to be opaloid in character.

The intimate association of the skarns and iron-ore masses and the composition of the former suggest a common genesis, because the chief additions to the limestone have been silica and iron. There is little doubt that the iron-ore was deposited from solution and not as a result of pneumatolytic action, the high-temperature mineral magnetite being very sparingly developed.

Goldschmidt,[3] in discussing the origin of the Kristiania skarns, put forward the view that the iron and most of the silica was introduced from the magma as volatile compounds, the development being accomplished by a pneumatolytic replacement. He was of the opinion, however, that some silica may have been introduced by solutions at a later stage. The evidence of the Marulan contact seems to favour the view that the skarns developed at the hydatogenetic stage of the crystallization-history of the intrusion. Thus the intimately associated ores are ironstones, and there is an absence of typical pneumatolytic minerals and ores. It is well-known that a very definite paragenesis is shown by the metalliferous deposits directly associated with an intrusive mass, the pneumatolytic suite being of early origin, and of more restricted occurrence than the hydatogenetic suite, which form at lower temperatures.

Thus it is concluded here, that on the basis of the evidence from

[1] *Vid. Selsk. Skrifter*, 1911, No. 1, 213.
[2] *Bull. Geol. Comm. Finland*, 1914, 252.
[3] Loc. cit., 214–16.

attendant phenomena, one must regard the development of the skarns as due to metasomatic replacement of the limestone by solutions rich in silica and iron. The CO_2 expelled at the time of replacement may have had some effect in causing alteration of the already solidified rocks, such as the kaolinization of vesuvianite.

Now the petrographical evidence shows that the limestone was recrystallized prior to metasomatism, so that the presence of a fairly simple andradite-hedenbergite skarn points to the former existence of almost pure limestone. Any magnesia content would have been taken up as diopsidic-content in the hedenbergite.

The occurrence of wollastonite in specimen T. 100 is of some interest. This may be explained either as a result of crystallization during the first, thermal metamorphism, and therefore prior to metasomatism, or as due to the processes which produced the skarns. The former alternative is supported by the fact that the wollastonite is rather strongly altered, particularly by the deposition of iron-oxide in cleavage-cracks. On the other hand it must be pointed out that wollastonite occurs quite frequently in skarns of other regions, as for example in Kristiania, and apparently in such cases the supply of silica and iron to the limestone has been effected at temperatures which promote the development of wollastonite.

The andradite of some of the skarns contains a certain amount of grossular in isomorphous mixture. This would indicate that aluminous material in the sediments united with limestone to produce grossular, which was later made over into andradite-garnet during the metasomatism.

Before concluding this section it is pertinent to refer to T. 68—a rock transitional between the hybrid-zone and the skarn-zone—in which, under the microscope, one can see evidence to show that the sericitization of the hybrid rocks had been accomplished before the metasomatism which produced the skarns.

Assimilation of Lime and the Development of Hybrid Rocks.

As is frequently the case where limestone is intruded by plutonic masses, there has been some assimilation of sediment by the magma at the Marulan contact. This has produced an interesting marginal phase in the quartz-monzonite, which, it must be emphasized, is strictly limited, there being no evidence of extensive assimilation. The rocks forming the hybrid zone are rich in diopside and grade into skarns on the exterior of the intrusive. In places they are found forming tongues in amongst coarse marble, as seen along the traverse A–C, and may even surround inclusions of skarn. On the interior margin of the hybrid-zone there is much soil obscuring the passage into normal quartz-monzonite, but there is justification for assuming a very restricted lateral development of the hybrid rocks.

The texture of these diopside-rocks is essentially the same as that of the monzonite, and their appearance in hand-specimen suggests an igneous origin. Mineralogically, however, they present a striking contrast with the normal igneous rock. Plagioclase is about as abundant, and orthoclase is a little less so, but the ferro-magnesian content is entirely pyroxene which supplants the hornblende and biotite of the quartz-monzonite. A little interstitial quartz is present in one or two cases; at other times it is intergrown with prehnite which is prominently developed in most cases. Another notable feature is the splendid development of sphene, which has been described above, while lastly, there is some fairly clear calcite in intergranular spaces, suggestive of magmatic crystallization.

The rocks have been affected strongly by magmatic alteration whereby considerable quantities of clinozoisite-epidote have replaced some of the plagioclase, and abundant sericite and some chlorite have developed. In addition strong kaolinization of orthoclase has occurred.

The relation of the hybrid rocks to the normal type may now be stated. The lime-soda felspar, which certainly crystallized before the orthoclase, is a little more basic (An_{44}), than that of the quartz-monzonite, this just possibly being related to an excess of lime. Orthoclase is not quite so abundant as in the normal rock, but possesses the same general features, except for its passage into kaolin and sericite. The kaolinization may have been carried out by cognate magmatic gases or by the CO_2 released from the limestone. Eckermann[1] has indicated the possibility of important action due to the influx of this gas from limestone into a magma, and Boydell [2] has also commented upon this.

In the quartz-monzonite the iron is present partly in the silicates, hornblende and biotite, and partly in pyrites, magnetite and derivative haematite; the magnesia, of course, being contained in the hornblende and biotite also. There is no sphene and the iron-ore is not ilmenitic.

Now in the hybrid rocks the magnesia has been taken up in diopside which is not iron-bearing, and only occasionally aluminous (see petrographical section). The iron has crystallized as ilmenite and from this, sphene has developed by the action of the lime-rich magma. This is clearly shown by the frequent occurrence of ilmenitic nuclei in sphene, the periphery of the latter being concentric with the borders of the ilmenitic cores. These assumptions lead to the question of the origin of the titanium for the production of sphene and ilmenite. Now the decomposition of the biotite in the quartz-monzonite shows that this mineral contains an appreciable amount of titanium, and thus in the hybrid rocks

[1] *Geol. Fören. Stockholm Förh.*, 1923, Nov.–Dec., 524–6.
[2] *Trans. Inst. Min. Met.*, xxxvii, 1928, 69.

this titanium has united with iron to give ilmenite; biotite, of course, being absent. The ilmenite, so formed, has been partly resorbed to produce sphene. A consideration of the relative amount of sphene in the hybrid type and of the titanium in the biotite in the normal rock, based upon some collateral chemical evidence from Woolnough's paper, shows that the hypothesis just postulated is feasible.

Following the crystallization of the plagioclase, diopside, sphene and orthoclase in the hybrid rocks, the pneumatolytic stage was reached, when abundant sericite was formed, both felspars succumbing to the action of gases. A certain amount of chloritization may have been carried out at this time. Succeeding this came the late-magmatic stage and certain reactions (termed deuteric by Sederholm) were initiated. These include the development of chlorite and masses of clinozoisite-epidote. About this time, also, prehnite crystallized separately or as intergrowths with quartz, and prehnitization of plagioclase took place. Perhaps the latest crystallization of all in the hybrid rocks was that of calcite, this being possibly the last expression of the CO_2, which was expelled from the limestone during assimilation.

Thus the evidence of assimilation of lime by the quartz-monzonite is to be seen in the development of hybrid rocks which show the following features: the absence of hornblende and biotite and the presence, in their stead, of lime-rich pyroxene; a relative abundance of sphene, a slightly more basic plagioclase, and a strong development of prehnite which was held up till the late-magmatic stage.

The effects of assimilation in this Marulan contact differ from those described for the contact at Concepción del Oro, in that garnet does not occur as an endogenic product in association with the diopside of the former locality.

Summary.

1. The contact metamorphic effects produced by the intrusion of quartz-monzonite into the Silurian limestone of the Marulan district, New South Wales, are described.

2. The rocks are divided broadly into marbles, hornfelses, skarns, and hybrid diopside-rocks. The first two groups are interpreted as being due to the recrystallization of limestone containing impurities which have reacted with the lime of the sediments to give lime-silicates and certain other minerals. The view is taken that only a very minor amount of pneumatolytic metamorphism followed the main thermal change. The skarns are shown to be due to the metasomatic replacement of recrystallized limestone by magmatic solutions rich in iron and silica, which were also responsible for the deposition of iron-oxides in cracks.

The hybrid rocks are explained as developing from limited marginal assimilation of limestone by the quartz-monzonite magma.

3. The textures and minerals of the rocks are described, some very interesting petrographical details being recorded. The mineral assemblages are then considered from the standpoint of their genesis, brief chemical considerations being made.

Acknowledgments.—The author wishes to express his indebtedness to Dr. A. Harker for helpful discussion, and to Dr. C. E. Tilley for confirmation of petrographical determinations and critical discussion during the work. Also, he is grateful to Professor A. Hutchinson for permission to work in the Mineralogical Laboratory, Cambridge, and to several others who have kindly assisted in various ways.

Further, he wishes to point out that it has been possible to do this research in the Sedgwick Museum, Cambridge, only as a result of financial help from the Australian National Research Council, the Australian Council of Scientific and Industrial Research, and the Longworth Trust, Newcastle.

EXPLANATION OF PLATE XII.

FIG.

1.—Grossular-wollastonite hornfels. Idioblasts of grossular with dodecahedral development are surrounded by mostly small crystals of wollastonite, which have been pushed aside by the growth of the former. Crossed nicols. × 24 diameters. T. 108.

2.—Vesuvianite-phlogopite marble. The constituents are subidioblastic vesuvianite, and irregular calcite and phlogopite, with a little iron-oxide. Ordinary light. × 23 diameters. T. 93.

3.—(*a*) Grossular-wollastonite-diopside hornfels. The minerals are marked on the photograph. Note the subordinate character of the pyroxene. Ordinary light. × 24 diameters. T. 72.

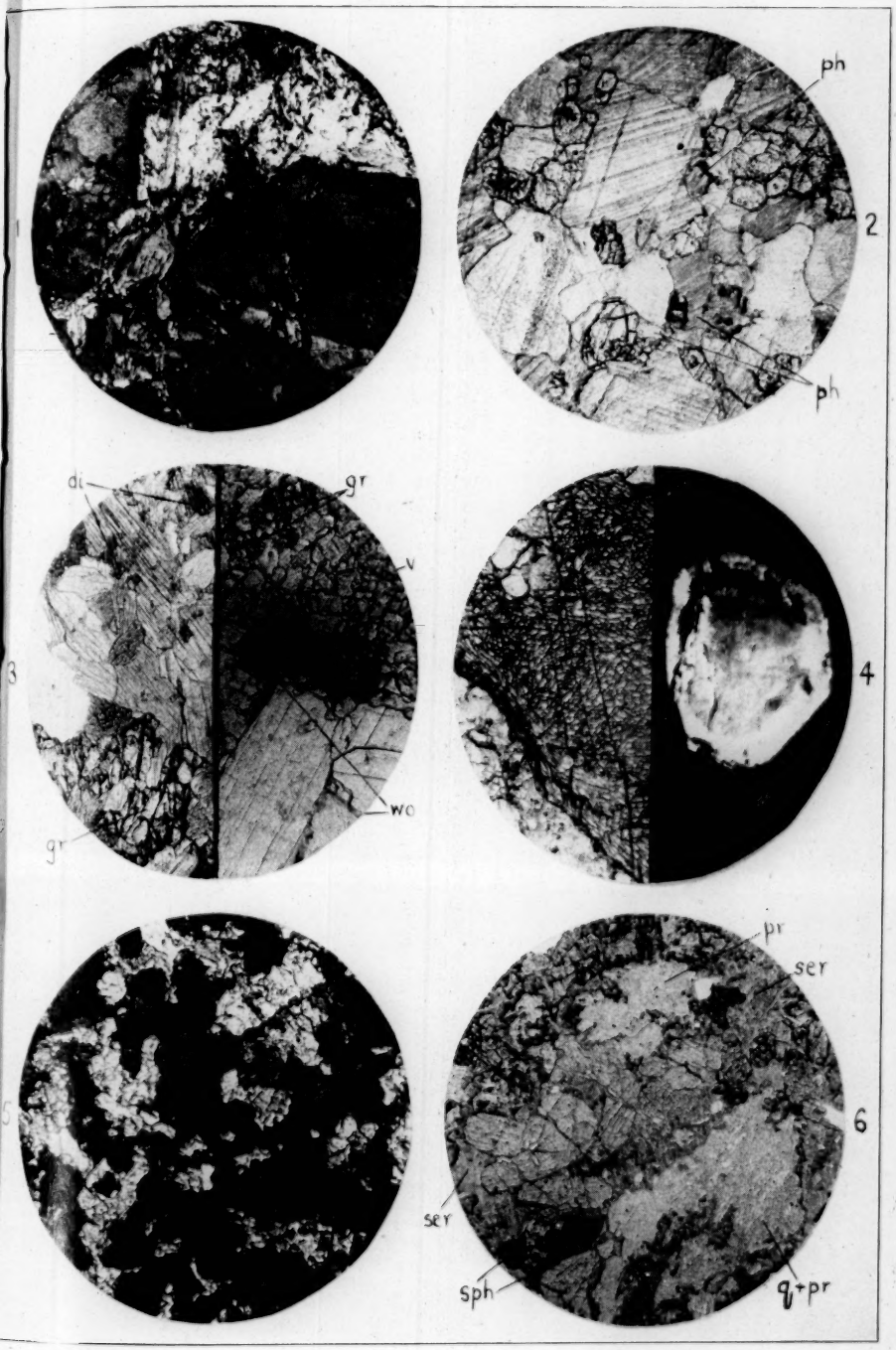
(*b*) Grossular-wollastonite-vesuvianite hornfels. Grossular is seen towards the top showing stronger relief than the vesuvianite. The wollastonite is present in longitudinal and transverse sections, the latter showing the presence of the (100), (001), (101), and ($\bar{1}$01) faces. Ordinary light. × 25 diameters. T. 105.

4.—(*a*) Part of wollastonite crystals showing cleavage parallel to (101), in addition to the (001) and (100) cleavages. The last two form a reticulated pattern, the (100) development being the stronger. Ordinary light. × 23 diameters. T. 73.

(*b*) Zoned crystal of vesuvianite from typical calc-silicate rock. Crossed nicols. × 69 diameters. T. 73.

5.—Andradite-hedenbergite skarn showing diablastic intergrowth of the two minerals, the pyroxene being light, and the garnet extinguished. Crossed nicols. × 25 diameters. T. 67.

6.—Contaminated igneous rock from the margin of the quartz-monzonite intrusion. Constituents are orthoclase, with inclusions of apatite, in the centre of the field; sericitized plagioclase (ser), diopside, sphene with ilmenite nucleus (sph), and prehnite (pr); the last intergrown with quartz in the lower right-hand portion of the photograph. Ordinary light. × 23 diameters. T. 96.



Microphotographs of Rocks from Marulan, New South Wales.

[To face p. 314.

The Geology of Skerryvore, Dubh Artach, and Sule Skerry.

By Frederick Walker, M.A., D.Sc., University of St. Andrews.

THE three rocky islets which form the subject of the present paper occur in Scottish waters, Skerryvore and Dubh Artach lying off the mouth of Loch Linnhe, between Tiree and Colonsay (Fig. 1), while the situation of Sule Skerry is still more remote, being 37 miles N.N.E. of Cape Wrath (Fig. 2). They are all exposed to the waves of the open Atlantic and have been the cause of many disastrous shipwrecks. The erection of lighthouses on each of them has, however, rendered them finally a guide rather than a danger to navigation. This has also brought them within reach of the geologist, and the kindness of the Commissioners for Northern Lighthouses in granting him passages enabled the writer to visit all three islands in the summer of 1930.

Besides having an intrinsic geological interest the islets yield important clues as to the nature of the rocks submerged by Scottish coastal waters. None of them appears to have undergone a detailed investigation, though brief notes on their geological nature appear in several publications.

Skerryvore.

Skerryvore (the great reef) is one of a cluster of reefs extending over a distance of 4 miles (lat. 56°19′, long. 7°6′). At high tide only a few rocky knobs project above water, the lighthouse being situated on the largest of them ; but at low tide a double island measuring over all 170 yards north-south by 80 yards east-west is exposed. A geo trending E.N.E. separates the island into two portions, the lighthouse being built on the north and larger one, which reaches a height of 6 feet above high tide mark.

The only geological description of Skerryvore known to the writer, is that given by A. Stevenson, in his classic work on the lighthouse.[1] He describes the rock as a " syenitic gneiss " with quartz, felspar, hornblende and mica, and calls attention to the high polish imparted to it by wave action. He also records the presence of a dyke of basalt in Ritson's Gully and mentions the occurrence of indurated guano on the rock. This deposit he considers to have been formed by sea birds at a time when the reef was more extensive.

In the published map of the Geological Survey (sheet 42, one inch = one mile) Skerryvore is shown as a grey hornblende-biotite-gneiss or pyroxene-gneiss cut by a thick north-west dyke of dolerite.

The writer found Skerryvore to consist of smooth grey and black gneiss, with well-marked regular banding, having its foliation

[1] A. Stevenson, *Account of the Skerryvore Lighthouse*, 1848, 32–3.

planes almost vertical, and striking north-south. In places the gneiss was found to include flesh-coloured bands of felspathic material and veins of greasy opalescent quartz. The dark bands, which have almost the appearance of a hornblende-schist, were also found to attain locally a thickness of a foot or more. In the northern portion of Ritson's Gully the dyke recorded by Stevenson is well exposed. It is two feet wide and consists of a fine-grained vesicular olivine-dolerite with tachylytic selvages. The trend follows the strike of the gneiss, being roughly north-south. No trace was found of the thick north-west dolerite dyke, shown on the Geological Survey maps, but the writer's visit to the island took place at half-tide when much of the rock is under water.

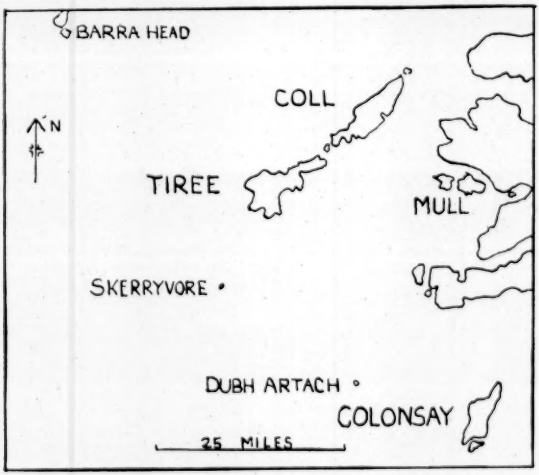


Fig. 1.

Gneiss.—Under the microscope, the gneiss of Skerryvore is seen to be of acid composition. The light bands are made up of a mosaic of quartz, orthoclase and acid plagioclase, and these minerals, to the surprise of the writer, were also found to predominate in the black bands, though accompanied by a considerable proportion of biotite and hypersthene. Hornblende was not recorded in any section, but apatite, in large crystals, and magnetite form abundant accessories. In some of the light bands quartz is more abundant than felspar, but the reverse is often the case and the resultant felspathic bands frequently have a pinkish colour. The grain of the gneiss is variable ; the light minerals are distinctly larger than the dark and seldom exceed 4 mm. in length.

Evidence of shearing stresses is found throughout the rock. In the light bands the quartz is full of strain-shadows, is traversed

by shear-planes, and has suffered well-marked marginal granulitization. The more resistant felspar, which consists of orthoclase and finely-twinned oligoclase-albite, is only very slightly granulitized, but shows distinct flexures of the twin-planes. In the dark bands the biotite, which occurs in small flakes of a cold reddish-brown colour, plays the part of a cement to the grains of quartz and felspar, but is relatively small in amount. Hypersthene, with distinct pink-green pleochroism, occurs very sporadically in smallish grains, and all the minerals are smaller in size than in the light bands. In some cases the biotite branches off to form thin sinuous veins in the white minerals, and Professor Bailey, on seeing the writer's sections, pointed out that the habit of the mica in this case is reminiscent of the gneiss of Inishtrahull recently

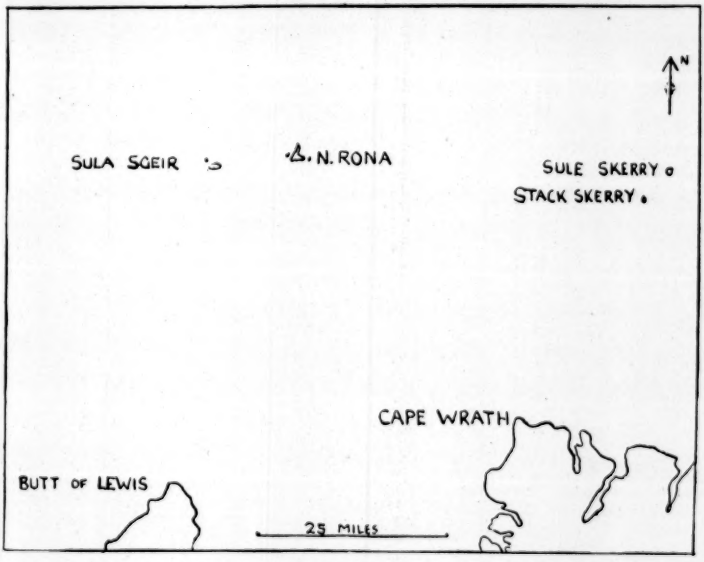


FIG. 2.

described by Dr. W. J. McCallien.[1] Here the mineral is thought to have arisen by contact alteration of chloritic decomposition products by an underlying granite mass, and there seems a strong probability that all the Skerryvore biotite was formed in similar fashion. The habit of the mineral is most suggestive of migratory chlorite, and its extreme freshness might well be accounted for by thermal recrystallization. The mere fact that Skerryvore projects above the waves at all is very possibly due to the occurrence of a great granite mass below, which would alter it just as the gneisses of Iona have been altered by the Ross of Mull granite.[2]

[1] W. J. McCallien, GEOL. MAG., LVII, 1930, 545.
[2] T. J. Jehu, *Trans. Roy. Soc. Edin.*, liii, 173.

The published maps of the Geological Survey show clearly that Skerryvore represents the south-west production of the structural line formed by Coll and Tiree, this having the confirmation of soundings. The Tiree Memoir has not yet appeared and the full advantages of a comparison with that island cannot, therefore, be reaped. The writer has, however, benefited by discussion with Professor Bailey, who agrees with him in assigning a sedimentary origin to the Skerryvore gneiss, though the critical examination of a chemical analysis would be necessary to put the matter beyond doubt.

Dyke.—The thin dolerite dyke in Ritson's Gully displays features found in many other Scottish Tertiary olivine-dolerites. In the hand specimen, the rock is seen to be a fine-grained, black olivine-dolerite with a well-marked platy fracture. Microscopically, plagioclase is the most conspicuous constituent, occurring in slender laths up to 0·5 mm. in length. It is mainly medium labradorite (Ab_1An_2), but the laths are zonal and there is also a fair amount of more acid plagioclase in broader laths of later crystallization. The pyroxene occurs in sub-ophitic crystals which rarely exceed 0·4 mm. across. It is a strong purplish-green in colour, but pleochroism is slight. Olivine in shapeless grains up to 0·4 mm. in diameter is common and is usually converted entirely to serpentine or calcite: the central portions of some grains are, however, quite fresh. Small crystals of magnetite are abundant, and needles of apatite may be detected everywhere under the high power. Circular vesicles with centres of calcite and margins of serpentine are common and both these minerals seem to have been deposited extensively throughout the rock. The approximate mode is given below.

olivine	10
augite	16
plagioclase	48
magnetite	6
calcite and serpentine	20

Dubh Artach.

About 8½ miles south-east of Skerryvore lies Dubh Artach (56° 8′ N. by 6° 38′ W.). The etymology of the name is doubtful, but the interpretation—Dubh Hirtach, "the black deadly one"—given by Professor Watson,[1] is probably the most satisfactory. The rock is roughly oval in shape, with a major diameter of 250 feet, and reaches a height of 47 feet above high tide mark. It forms the highest and most easterly of a series of reefs which stretch out to the west for nearly half a mile. In spite of its considerable height, Dubh Artach is devoid of land vegetation, for during storms it is swept by waves from end to end.

[1] W. J. Watson, *Celtic Place Names of Scotland*, 1926.

In the Colonsay Memoir, Mr. E. H. Cunningham Craig [1] refers briefly to Dubh Artach, stating that it is probably an intrusive dolerite, but that no junctions are seen with other rocks. In the corresponding geological map (sheet 35) it is marked (D ?).

The irregular columnar nature of the reefs is very evident and they appear to be part of an almost horizontal sill. The rock in the hand specimen is seen to be a greyish-black to green olivine-dolerite of medium grain. Neither vesicles nor segregation veins were found in it, and it shows very little variation throughout the exposure.

Microscopically, the rock is a medium-grained ophitic olivine-dolerite. The felspar is largely a basic plagioclase with well-marked twinning on the Carlsbad and albite laws. Pericline twinning is much rarer. The most basic variety found was a medium labradorite (Ab_1An_2), but the crystals show well-marked zoning and may grade into oligoclase at the margin. The felspar forms elongated laths of very variable size with a maximum length of 2 mm. There are, however, broader plates of more acid plagioclase, which are penetrated by the elongated laths and in which twinning is less developed. These have a refractive index lower than nitro-benzene (1·555), apparently consisting of oligoclase-andesine, and the relatively high alkali content of the rock (shown in the analysis below) is doubtless due to their presence.

The pyroxene of the rock is the greenish-brown augite, so characteristic of many Scottish olivine-dolerites of Tertiary age, showing slight pleochroism and numerous fluid inclusions arranged in bands. Zoning is inconspicuous or absent, while the extinction angle is 43°. This pyroxene bears a highly developed ophitic or poikilophitic relationship towards the plagioclase forming irregular clumps up to 5 mm. across. It is, on the whole, less abundant than is usual in Tertiary olivine-dolerites.

Olivine in shapeless grains, some of which appear to be sub-ophitic, is still less abundant and is completely altered to green or yellow serpentine. Much of this serpentine having migrated through the rock, the proportion of olivine originally present is difficult to estimate. Large clumps of skeletal or ophitic ilmenite, often 2 mm. in diameter, are the only other major constituent, but small apatites form an abundant accessory. Analcite appears to be altogether absent.

An analysis of the rock together with the norm and approximate mode is given on p. 320.

The analysis shows the rock to be richer in alkalies and alumina and poorer in magnesia than the average Tertiary crinanite or ophitic olivine-dolerite, to which the Dubh Artach dolerite has a marked mineralogical resemblance. These differences are reflected in the high felspar and low ferromagnesian percentage of both

[1] *Mem. Geol. Survey*, "Colonsay and Oronsay," 1911, 95.

norm and mode. The plagioclase-augite ratio is 4·7 as against 2·5 and 2·2 in the Shiant crinanites,[1] and the Fladdachuain [2] olivine-dolerite respectively. Potash reaches a relatively high percentage in the analysis, and the acid plagioclase doubtless contains a considerable proportion of orthoclase in solid solution, but this is an unusual feature in a Tertiary olivine-dolerite.

Analysis.		*Norm.*		*Mode.*	
SiO_2	47·29	orthoclase	10·6	olivine	7
TiO_2	1·89	albite	25·4	augite	15
Al_2O_3	17·74	anorthite	27·8	plagioclase	70
Fe_2O_3	5·04	nepheline	1·9	ilmenite	7·5
FeO	5·11	diopside	13·2	apatite	0·5
MnO	0·10	olivine	7·2		
MgO	5·67	ilmenite	3·7		
CaO	9·72	magnetite	7·2		
Na_2O	3·42	apatite	1·3		
K_2O	1·78				
H_2O+	1·25				
H_2O-	0·85				
P_2O_5	0·60				
	100·46				

Analyst, N. Sahlbom.

There is, of course, no direct proof of the age of Dubh Artach, neither can one write it down definitely as a sill. The grain, however, is distinctly coarser than is the case in any British basic lava flow which has been described, and the intrusive nature of Dubh Artach cannot, therefore, remain in much doubt. The absence of slagginess and vesicularity in the considerable thickness exposed is also against its being a lava.

The available bathy-orographical maps show that it has no structural connection with any of the neighbouring islands, but it is less than 25 miles from a great centre of Tertiary igneous activity in Mull, and doubtless bears the same relation to it as the Maddies and the Shiant Isles [3] bear to the Skye focus.

Sule Skerry.

Although the situation of Sule Skerry (59° 5′ N. by 4° 23′ W.) is much more remote than that of the other two rocks, this northern islet is in every way more habitable. The name may mean the "eye skerry", the "sail skerry", or the "gannet skerry". Gannets do not, however, breed on Sule Skerry at the present time, though they are abundant on its westerly neighbour, Sula Sgeir. Sule Skerry measures 850 yards in length, from east to west, while its greatest breadth from north to south is 550 yards. It is cut

[1] F. Walker, *Quart. Jour. Geol. Soc.*, lxxxvi, 1930, 375.
[2] F. Walker, *Trans. Roy. Soc. Edin.*, lvi, 763.
[3] F. Walker, *Quart. Jour. Geol. Soc.*, lxxxvi, 1930, 393.

into deeply on all sides by numerous geos, which have a variable trend and form admirable landing places. The highest point of the island is 40 feet above high tide mark.

The flat centre of the island is thickly covered by camomile and goosefoot, which decay to form a dark brown loamy soil. Though this soil looks perfectly easy to traverse, it is not so in practise, for the thousands of puffins which inhabit the island have tunnelled it in every direction, and a single unwary step may result in a twisted ankle. Besides puffins—shags, arctic terns, and stormy petrels breed abundantly on the island.

In the *North Sea Pilot*,[1] Sule Skerry is described as "highly stratified gneiss", and, indeed, the stratiform appearance of the rock is its most conspicuous feature, the division planes having a constant south-west dip of 30°–40° over the whole island.

The rock itself was found to show very little variation in the field, specimens from all parts being indistinguishable. It is greyish-white gneiss with irregular greenish-black streaks. Occasionally it is traversed by crushed pinkish felspathic veins and by shatter-belts, which have in many cases given rise to the geos, the Atlantic breakers quickly seeking out any line of weakness.

Under the microscope the structure of the rock is found to present peculiarities. The light portion, which forms the bulk of the rock is, taken by itself, monomineralic, being an andesine-anorthosite.

The andesine has a mean refractive index of $1{\cdot}552 \pm {\cdot}003$ and occurs as an even mosaic of crystals, which measure up to 3 mm. across. They show very well developed twinning on the albite and pericline laws, but the twin planes sometimes show slight flexures, or the crystals may even be traversed by sharply-defined shear-planes. The plagioclase is usually quite unaltered.

The dark streaks consist of groups of small hornblende prisms and grains of quartz. The amphibole is bluish-green in colour, is strongly pleochroic and usually occurs in well-formed elongated prisms up to 0·5 mm. in length with extinction angle of 18°. The quartz occurs in small grains, generally enclosed by hornblende prisms, and is subordinate in amount. Alteration of the amphibole to chlorite or carbonates is common. Apatite is an abundant accessory.

The curious feature of the dark streaks is that they appear to have been intruded into the solid anorthosite in liquid form. They break across the andesine crystals everywhere and frequently send veins into the felspar. Now a quartz-hornblende rock is not a normal igneous type and the conclusion seems unavoidable that the injection of the dark bands took place at exceedingly great depth, where immense pressure gives rise to different mineral associations (as in the eclogites), or that complete recrystallization of the dark bands has taken place with the formation of new minerals.

[1] *North Sea Pilot*, 1895, **2**, p. 25.

Contact alteration caused by some underlying plutonic mass might cause this recrystallization as in the case of Skerryvore and Iona, but the writer inclines towards the first hypothesis. There can at least be no doubt that the gneiss of Sule Skerry is a composite rock formed in two distinct stages.

An analysis of the gneiss made by Dr. N. Sahlbom, is given below, together with one of an anorthosite-norite from New York State for comparison.

	A.	B.
SiO_2	53·74	54·47
TiO_2	0·08	—
Al_2O_3	24·39	26·45
Fe_2O_3	0·63	1·30
FeO	2·52	0·67
MnO	0·03	—
MgO	2·67	0·69
CaO	9·47	10·80
Na_2O	4·77	4·37
K_2O	0·66	0·92
H_2O+	0·94	0·53
H_2O-	0·14	
P_2O_5	0·37	—
	100·41	100·20

A. Gneiss, west end of Sule Skerry. Analyst, N. Sahlbom.

B. "Norite," quoted from Washington's Tables, p. 303. Analyst, A. R. Leeds.

The two analyses show good agreement, but the Sule Skerry rock is slightly more femic, owing, no doubt, to the injection of the hornblende bands. Since the only ferromagnesian mineral in the rock is hornblende, no useful purpose is served by calculation of the norm.

Anorthosites have been recorded from the Lewisian formation of South Harris by Professor T. J. Jehu and Mr. R. M. Craig,[1] but the writer is unaware of any British rock which is comparable with the gneiss of Sule Skerry. It is probably of pre-Cambrian age, but it certainly bears no resemblance to the rocks of the mainland. It would be interesting, therefore, to obtain specimens from the relatively inaccessible islet of Stack Skerry which lies some five miles south-west of Sule Skerry, but this must perforce be left to some geologizing yachtsman to accomplish.

Summary.

Skerryvore consists of acid gneiss with dark bands containing biotite and hypersthene. The mica was probably formed by the recrystallization of chloritic matter by heat from an underlying plutonic mass. The islet is cut by a 2 foot north-south dyke of olivine-dolerite.

Dubh Artach forms part of a sill of ophitic olivine-dolerite and is probably of Tertiary age.

[1] T. J. Jehu and R. M. Craig, *Trans. Roy. Soc. Edin.*, lv, 471–3.

Sule Skerry consists of andesine-anorthosite into which dark streaks consisting of hornblende and quartz have been injected at a later date to form a banded gneiss.

ACKNOWLEDGMENTS.

The writer desires to express his indebtedness to Professor E. B. Bailey for many helpful suggestions, to Dr. W. J. McCallien for access to his sections of the Inishtrahull gneiss, to the Commissioners for Northern Lighthouses for passages granted to all three rocks, and to the Carnegie Trust for the Universities of Scotland for a grant which helped to defray the expenses of the investigation.

The Geology of the Farsan Islands, Gizan and Kamaran Island, Red Sea.

(*Continued from Vol. LXVIII, p.* 13.)

Part 3.—Echinoidea.

By A. G. BRIGHTON, M.A., F.G.S., Sedgwick Museum, Cambridge.

THE classification and nomenclature here adopted is that of Clark (1925), which should be consulted for the early literature; only those references which give recognizable figures are here quoted, although an attempt has been made to interpret the identifications given by Fourtau. The investigation has been facilitated by the collection of recent echinoids made by Dr. Macfadyen in the Farsan Islands; and my thanks are also due to Mr. C. C. A. Monro for permission to examine material in the British Museum (Natural History).

The identifications and horizons are :—

		Marly Limestone Series.	
	Reef. Limestone.	White Limestone.	Basal Beds.
Echinometra mathaei . .	*	*	
Heterocentrotus mammillatus .		*	
Clypeaster humilis . .	*	*	
C. (*Rhaphidoclypus*) *reticulatus*	*	*	*
Laganum depressum . .	*	*	*
Fibularia craniolaris . .			*
Paraster gibberulus . .		*	*
,, *savignyi* . .		*	*
Brissus latecarinatus . .	*		?
Maretia ovata . . .			*

All these species are living in the Indo-Pacific area (Clark, 1925); all except *Fibularia craniolaris* are recorded by Fourtau (1904, p. 444; 1914, p. 88)[1] from Raised Beaches in the Red Sea area: *Clypeaster reticulatus*, *Laganum depressum*, and *Maretia ovata* are known definitely from the Pliocene (Stockley, 1927; Currie, 1930); and if (as suggested below) *C. suffarcinatus* is a synonym of *Clypeaster humilis*, this species also occurs in the Pliocene. Fourtau (1914, p. 89) states that *Laganum depressum* and *Maretia planulata* (= *M. ovata*) are no longer living in the Red Sea.

The distribution in time of the Echinoids thus agrees with that of the Mollusca (see Part 2), except that none of the former are extinct. There is therefore nothing to add to the discussion of the age of the beds given in Part 2 (p. 4); they are probably Pleistocene, and in any case cannot "be much older than Pleistocene".

Echinometra mathaei (de Blainville).

1873. *Echinometra lacunter* (Leske), A. Agassiz, *pars*, pl. iv*b*, fig. 4.
1904. ,, ,, (Linné), Fourtau, pp. 415, 444.
1914. ,, ,, Blainville, Fourtau, p. 88.
1925. ,, *mathaei* (de Blainville), Clark, p. 143.

Material.—Reef Limestone: Zifaf Island (C 71)[2]; Seir Peninsula, Farsan Kebir.
White Limestone: Ras Hassis, Farsan Kebir (C 72, 73).

Discussion.—These six specimens are indistinguishable from denuded recent examples from the Farsan Islands. The fossils have four pore-pairs in each compound plate, the living forms four or five. Clark (1925, p. 144) states that "there is no reliable distinctive feature in specimens which have lost spines, pedicellariae, and tube-feet" by which *E. mathaei* and *E. oblonga* (de Blainville) may be distinguished; but the fossils do not possess the large adapical primary tubercles which characterize the typical *E. oblonga*.

Since *E. lacunter* (Linné) as interpreted by Clark is an American and tropical Atlantic species, it is probable that the specimens identified as *E. lacunter* by Fourtau are examples of *E. mathaei*.

Heterocentrotus mammillatus (Linné).

1873. *H. mammillatus* (Klein), A. Agassiz, p. 428, pl. iiic.
1904. ,, ,, ,, Fourtau, pp. 414, 444.
1912. ,, ,, (Brandt), Clark, p. 378, pls. cxv–cxvii.
1925. ,, ,, (Linné), Clark, p. 147.

Material.—White Limestone: Ras Hassis, Farsan Kebir.

Discussion.—A fragment, without apical disc or peristome, agrees in all its features with a recent specimen from Hurghada, Red Sea.

[1] Fourtau sometimes employs different names from those adopted here; see the synonymy given later for each species.

[2] C followed by a number, in parenthesis, after a locality, indicates the catalogue number of the specimens in the Sedgwick Museum; all the remaining specimens are in the British Museum (Natural History).

Clypeaster humilis (Leske).

1904. *C. rosaceus* (Linné), Fourtau, p. 420, text-fig. 1 ; p. 444.
1914. *C. humilis* (Leske), Clark, p. 36, pl. cxxxvii ; pl. cxxxviii, fig. 4.
1914. *C.* sp., Fourtau, p. 102, pl. xi.
? 1916. *C. placunarius* Michelin, Fourtau, p. 85.
1922. *C. humilis* (Leske), Koehler, p. 51, pl. iii, figs. 1–5, 12.
1925. ,, ,, ,, Clark, p. 149.

Material.—Reef Limestone : Saso Island ; Gizan (C 74) ; Zifaf Island (C 75–6).
White Limestone : Dumsuk Island (C 77–8) ; Saso Island (C 79).

Discussion.—These forms are indistinguishable from a large series of recent specimens from the Farsan Islands. The examples from the White Limestone are small (reaching 53 mm. in length), while those from the Reef Limestone attain a length of 80 mm. The internal structure agrees with the figures given by Fourtau (1914) and Koehler (1922).

C. suffarcinatus Duncan & Sladen, from the Makrán Series (Pliocene) in the Persian Gulf (1886, p. 376, pl. lviii, Figs. 1–5), cannot be distinguished from some of the recent specimens of *C. humilis* from the Farsan Islands, which exhibit all the external characters mentioned by Duncan & Sladen as differentiating *C. suffarcinatus*. As they do not describe the internal characters, it is not certain that the two species are identical.

Clypeaster (*Rhaphidoclypus*) *reticulatus* (Linné).

1873. *C. scutiformis* Gmelin, A. Agassiz, p. 512, pl. xiii*f*, figs. 1–2.
1904. ,, ,, Lamarck, Fourtau, p. 422.
1914. ,, ,, Gmelin, Fourtau, p. 88.
1916. ,, ,, ,, Fourtau, p. 85.
1922. *Rhaphidoclypus reticulatus* (Linné), Koehler, p. 68, pl. vi, figs. 3–4.
1925. *C. reticulatus* (Linné), Clark, p. 151.
1927. ,, ,, ,, Stockley, p. 114, pl. xxi, fig. 7.
1930. ,, ,, ,, Currie, p. 175, pl. xvi, fig. 5.

Material.—Reef Limestone : Ras Hassis, Farsan Kebir (C 80).
White Limestone : Saso Island (C 81–4) ; Dumsuk Island (C 85).
Marly Limestone Series : Gebel Muhammad (C 86–9).

Discussion.—These twelve specimens possess the internal structure typical of the subgenus, and figured by Koehler (1922).

Laganum depressum L. Agassiz.

1841. *L. depressum* (Lesson MS.) L. Agassiz, p. 110, pl. xxiii, figs. 1–7.
1867. ,, ,, var. *sinaiticum* Fraas, p. 333, pl. vi, fig. 15.
1873. ,, ,, Lesson, A. Agassiz, p. 518, pl. xiii *f*, figs. 5–8.
1886. *L. tumidum* Duncan & Sladen, p. 379, pl. lviii, figs. 6–10.
1894. *L. fragile* Mazetti, pp. 217–18, text-figs. *a–d*, [non Bittner].
1894. *L. delicatum* Mazetti, p. 248, text-figs. *a–d*.
1914. *L.* sp. Fourtau, pl. xii, fig. 1.
1922. *L. depressum* Lesson, Koehler, p. 88, pl. ix, figs. 1, 2, 7, 8 ; pl. xiii, fig. 3.
1925. ,, ,, Agassiz, Clark, p. 157.
1927. ,, ,, ,, Stockley, p. 115, pl. xxi, figs. 5*a*, *b*.
1930. ,, ,, ,, var. Currie, p. 175, pl. xvi, fig. 4.

Material.—Reef Limestone: Dumsuk Island; El Gabr, Farsan Kebir; Kamaran Island; Khella, Farsan Kebir; Seluba Island; Zifaf Island (C 129–32).
White Limestone: Dumsuk Island (C 125); Saso Island (C 126); Zifaf Island.
Marly Limestone Series: Gebel Muhammad; Gebel Mukhezin (1 km. towards Huseyin Village), Farsan Kebir; Gebel Uzbah, Seir Peninsula, Farsan Kebir (C 127); Gebel Buttan, Seir Peninsula; Cliff facing Dumsuk Island, Seir Peninsula; Gizan (C 128).

Discussion.—This species is represented by 725 specimens, showing considerable variation. Most agree with the figures of L. Agassiz (1841) and A. Agassiz (1873), with subpentagonal outline. The figures quoted in the synonymy give some idea of the variation in size, shape, tumidity of margin, and shape of the petals; but these characters vary independently and continuously, and do not afford a basis for dividing the species, nor for recognizing varieties. Among the elongated examples are forms resembling:—

(1) The type of *L. depressum* var. *sinaiticum* Fraas (from a 100 metre raised reef at Djebel Zeit) with pointed petals; and

(2) The type of *L. ellipticum* (L. Agassiz, 1841, pl. xxiii, Figs. 13–15) regarded by A. Agassiz as a synonym of *L. depressum* (1873, p. 138), with elliptical outline and more rounded petals; and

(3) The form described by Dr. Currie from the Pliocene of Mombasa Island, as *L. depressum* var. and intermediate between *L. depressum* and *L. ellipticum*.

L. tumidum, from the Pliocene of Khárak Island, Persian Gulf, was separated by Duncan & Sladen by differences of shape; but all the characters they mention (as well as the rather wide interporiferous areas) are found in some of the Farsan examples. The specimens from the Reef Limestone and the White Limestone reach 59 mm. in length, and are on the average larger than those from the Marly Limestone Series; the latter average about 25 mm. in length and include forms of 10 mm. in length which agree with the type of the living *L. delicatum* (= *L. fragile*) from the Red Sea, which Clark (1914, p. 45) has already suggested is a young example of *L. depressum*. *L. kamaranense* Cotteau (1888, pl. 268, p. ix, Figs. 14–16), from a raised beach at Kamaran, is distinguished by the position of its periproct, close to the margin.

Fibularia craniolaris (Leske). (Text-fig. 1).

1873. *F. ovulum* Lamarck, A. Agassiz, 1873, p. 507, pl. xiiie, figs. 1–3.
1914. *F. craniolaris* (Leske), Clark, p. 57.
1925. „ „ „ Clark, p. 163.
Material.—Marly Limestone Series: Cliff section (opposite Dushuk Island), Seir Peninsula, Farsan Kebir (C 105–19).

Discussion.—The interior of one specimen (C 119) has been cleaned, and the absence of internal radiating partitions proved. There appear to be few figures of this common and variable species,

but I have compared the specimens with recent examples of the same size, from the Gulf of Suez, in the British Musem (Natural History), which were named by H. L. Clark, and there is complete agreement. The length of the twenty fossil specimens (which are all immature) varies between 4·2 and 2·6 mm.; the width

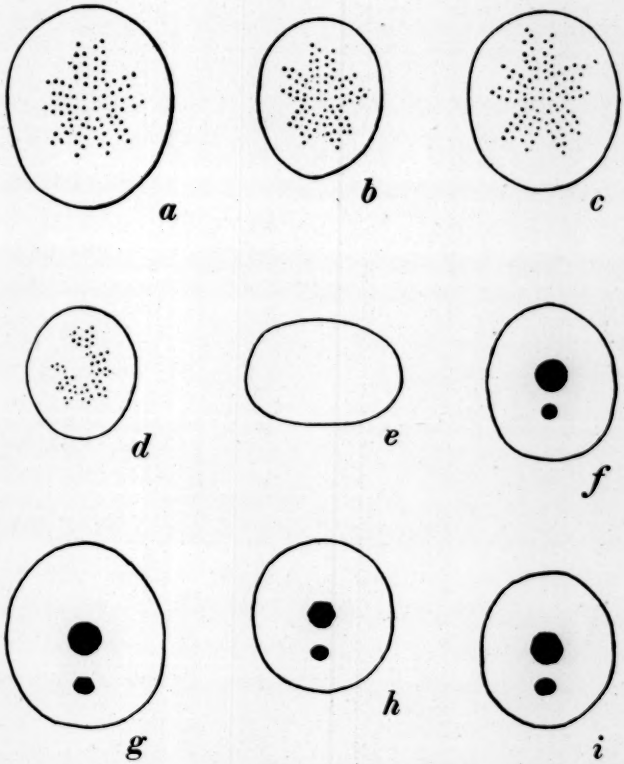


Fig. 1.—*Fibularia craniolaris* (Leske). Pleistocene (or (?) late Pliocene) Marly Limestone Series; Cliff Section (opposite Dushuk Island), Seir Peninsula, Farsan Kebir. × 20/3. Figs. *a–d*, specimens C 111–14; adapical views, showing variation in petals (the genital pores and parts of petals iii and iv are not decipherable in Fig. *d*). Fig. *e*, specimen C 115; lateral view. Fig. *f*, specimen C 116; *g*, C 117; *h*, C 115; *i*, C 118; adoral views, showing variation in shape, size, and position, of periproct and peristome.

(expressed as a percentage of the length) between 92 per cent and 80 per cent; the height between 62·5 and 75 per cent. The variation in the shape, and number of pore-pairs in the petals, and the shape and position of the peristome and periproct, are

shown in the Text-figures. The recent specimens collected by Dr. Macfadyen round the Farsan Islands are of normal size.

Paraster gibberulus (L. Agassiz and Desor). (Text-figs. 5–6.)

1904. *Schizaster gibberulus* Agassiz, Fourtau, p. 434, text-figs. 1*a*, *b*.
1908. ,, ,, ,, Fourtau, pp. 190–3, text-figs. 1–6.
1914. *Paraster* (*Schizaster*) *gibberulus* (Agassiz), Koehler, pp. 172–80.
1925. *Paraster gibberulus* (Agassiz & Desor), Clark, p. 202.
1925. *Schizaster bennacensis* Lambert, Lambert & Thiéry, p. 526.
1925. ,, *gibberulus* Agassiz, Lambert & Thiéry, p. 526.

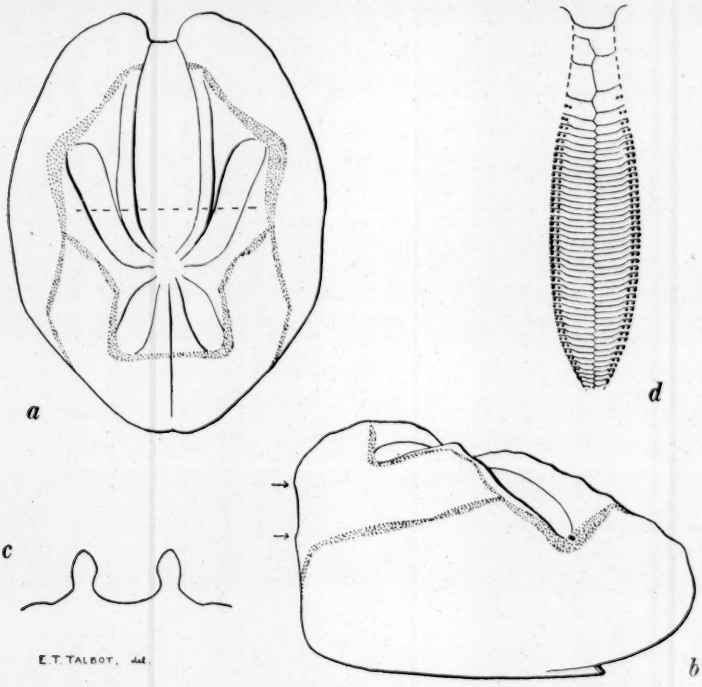


FIG. 2.—*Paraster savignyi* (Fourtau). Pleistocene (or (?) late Pliocene), Marly Limestone Series, Gebel Uzbah, Seir Peninsula, Farsan Kebir. Specimen C 102. Figs. *a*, *b*, *c*, natural size. Fig. *d*, × 3/2. Fig. *a*, adapical view, showing fascioles, the margins of the sunken ambulacral areas, and the carina on each side of amb. iii. Fig. *b*, lateral view; position of periproct indicated by arrows. Fig. *c*, section across petals ii, iii, and iv, along the dotted line in Fig. *a*. Fig. *d*, details of pores and sutures in amb. iii.

Material.—White Limestone: Dumsuk Island (C 90).
Marly Limestone: Series Gebel Uzbah. (C 91–5); Gebel Muhammad (C 97–8); Seir Peninsula (cliff facing Dushuk Island), Farsan Kebir (C 96); Gebel Mukhezin.

In addition to these thirteen specimens, thirty recent examples from the Farsan Islands have been examined, ranging from 41 to 18 mm. in length;

and four specimens (ranging from 28 to 17 mm. in length) from the 6 metre raised beach at Berbera, British Somaliland.

Discussion.—See *P. savignyi*, below.

Paraster savignyi (Fourtau). (Text-figs. 2–4.)

1904. *Schizaster savignyi*, Fourtau, p. 436, pl. i, figs. 4–5, text-figs. 2*a*, *b* (p. 434).
1904. ,, ,, var. *major* Fourtau, p. 439, pl. i, figs. 6–7.
? 1914. ,, ,, mut. *pleistocenica* Fourtau, p. 89, pl. viii.
1914. *Paraster* (*Schizaster*) *savignyi* Fourtau, Koehler, pp. 172–80, pl. viii, figs. 12–15; pl. ix, figs. 3, 11, 15.
1914. ,, ,, *gibberulus* (Agassiz), Koehler, pl. ix, figs. 1, 2, 16.
1925. ,, *savignyi* (Fourtau), Clark, p. 202.
1925. *Spatangus canaliferus* de Blainville, Lambert & Thiéry, p. 531.
1925. ,, *savignyi* (Fourtau), Lambert & Thiéry, p. 532.

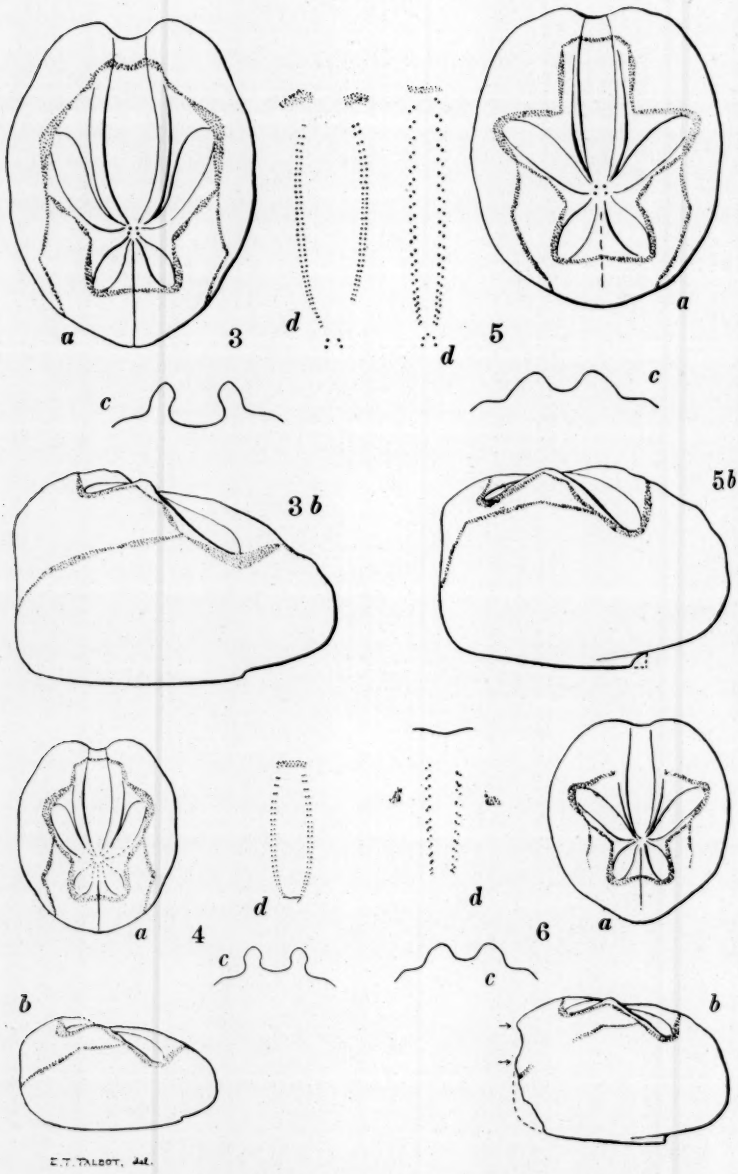
Material.—White Limestone: Dumsuk Island (C 99–100).
Marly Limestone Series: Gebel Uzbah, Seir Peninsula, Farsan Kebir (C 101–3); Gebel Muhammad (C 104).

In addition to these nine examples, ten specimens from the 6 metre raised beach at Berbera, British Somaliland, have been examined.

Discussion of P. gibberulus and *P. savignyi*.—From a study of the ample material at my disposal, it is possible to summarize the differences between these two species as interpreted by Fourtau (1904, 1908) as follows:—

		P. gibberulus	*P. savignyi*
Length		up to 40 mm.	up to 52 mm.
$100\frac{\text{Height}}{\text{Length}}$		usually above 70 per cent	usually below 70 per cent
Ambital notch		shallow	deep
Petal III.	cross-section	shallow	deep
	sides	not overhanging	overhanging
	pore-pairs	spaced	crowded
		unigeminal	sometimes irregularly bigeminal
		at 45° to transverse sutures	parallel to transverse sutures
	plates	high (average, 1 mm.)	low (average, 0·5 mm.)
Petals II and IV		divergent, slightly flexed	flexed

Most of these features (especially the shape of petals II and IV) are well seen in the protographs as reproduced by Fourtau (1904). The posture of the pore-pairs and their spacing in ambulacrum III



FIGS. 3, 4.—*Paraster savignyi* (Fourtau). Fig. 3, Gebel Uzbah, Seir Peninsula, Farsan Kebir; C 103. Fig. 4, Gebel Muhammad; C 104.

FIGS. 5, 6.—*Paraster gibberulus* (L. Agassiz and Desor). Fig. 5, Cliff section (opposite Dushuk Island), Seir Peninsula, Farsan Kebir; C 96. Fig. 6, Gebel Muhammad; C 97. All specimens from the Marly Limestone Series, Pleistocene (or (?) late Pliocene). Explanation as for Fig. 2.

of *P. gibberulus* is figured by Fourtau (1908, Text-fig. 5 [1]); that of *P. savignyi* is well shown in the figures given by Koehler (1914, pl. viii, fig. 13). The differences in the course of the fasciole across the paired anterior ambulacra in the two species (Figs. 3*a*, 5*a*), appear to be constant.

Clark (1925, p. 203) has suggested that "the differences between *P. savignyi* and *P. gibberulus* are very slight and it is doubtful if the two species can be maintained". From the short key that Clark gives, it appears that he relies mainly on differences of shape to differentiate the two species. In the specimens that I have examined, *P. savignyi* is usually more depressed and reaches a larger size than *P. gibberulus*; but the size and proportions are variable, and certainly do not form a reliable basis for separation. The essential differences in my opinion lie in the character of petal III (in particular, the spacing and posture of the pore-pairs), and the shape of petals II and IV. On this basis I have had no difficulty in deciding to which species any of the sixty-six specimens (even the smaller, below 30 mm. in length) should be referred. In the larger specimens of *P. savignyi*, petal III is often lanceolate. In medium-sized and small specimens, the pore-pairs of petal III are often strictly unigeminal; but they are always crowded and parallel to the transverse sutures, and thus quite distinct from the pore-pairs of *P. gibberulus*.

Schizaster savignyi mut. *pleistocenica* Fourtau (1914), from a raised beach of the Red Sea, differs from the recent *P. savignyi* only in the absence of the two anterior genital pores; thus simulating the common living species in the Mediterranean, *Ova canalifera* (Lamarck). Lambert and Thiéry (1925, p. 531), indeed, identify the specimen with the Mediterranean species which is known to them as *Spatangus canaliferus* de Blainville. The two anterior genital pores of *P. savignyi* are small, and are missing in the young specimen recorded by Clark (1925, p. 203) [2]; and it is at least possible that the type specimen of var. *pleistocenica* is an abnormal form of *P. savignyi* in which the anterior genital pores have never developed. If this is true, Fourtau's speculations (which were criticized and rejected by Lambert, 1915, Revue crit. Paléozool. Paris, pp. 78–80; and in Lambert and Thiéry, 1925, p. 529, footnote) concerning the origin of *P. savignyi* cannot be upheld.

P. savignyi var. *major* (Fourtau) from the Red Sea seems to be an extremely large form of *P. savignyi*, with which it agrees in all essentials as defined above. Koehler (1914, p. 179) asks if the

[1] This specimen, from the highest raised beach at Ras Bennas, has been made the holotype of *Schizaster bennacensis* Lambert (Lambert & Thiéry, 1925). From the figure and description given by Fourtau, it appears to be a true *P. gibberulus*, agreeing in all essentials with the recent specimens of that species which I have examined.

[2] Koehler (1914, pl. ix, fig. 14) records an immature *Paraster* with the right anterior genital pore missing.

differences between *P. savignyi* and *P. gibberulus* are more important than those between *P. savignyi* and var. *major*, and suggests that possibly all three belong to one species. It appears that Koehler is defining *P. gibberulus* and *P. savignyi* by differences of shape, and is ignoring the differences in petal III, which seem to me essential; the specimen figured by him (pl. ix, Fig. 1) as *P. gibberulus* (presumably partly because of its great height) possesses the petals and fasciole of *P. savignyi* and should be referred to that species.

Brissus latecarinatus (Leske).

1873. *Brissus carinatus* (Lamarck), A. Agassiz, p. 596, pl. xxi*a*, figs. 1–3.
1904. ,, ,, Gray, Fourtau, p. 444.
1914. ,, ,, ,, ,, p. 88.
1916. ,, ,, ,, ,, p. 89, pl. vii, fig. 4.
1925. ,, *latecarinatus* (Leske), Clark, p. 219.

Material.—Reef Limestone: Zifaf Island (C 120).
Marly Limestone Series: Gebel Buttan ?

Discussion.—Small specimens, such as that figured by Fourtau, and the one (length 39·8 mm.) from Zifaf Island, differ in the course of the posterior petals from large forms such as that figured by Agassiz; but the small forms can be matched exactly with recent specimens of the same size in the British Museum (Natural History). The two specimens from Gebel Buttan are internal casts, and their identity is therefore not certain.

Maretia ovata (Leske).

1873. *Maretia planulata* Gray, A. Agassiz, p. 570, pl. xix*b*, figs. 7–12.
1916. ,, ,, Agassiz, Fourtau, p. 89, pl. vii, fig. 3.
1925. ,, *ovata* (Leske), Clark, p. 226.
1927. ,, ,, ,, Stockley, p. 117, pl. xxi, figs. 8*a*, *b*.

Material.—Marly Limestone Series: Gebel Muhammad (C 121–2); Gebel Uzbah, Seir Peninsula, Farsan Kebir (C 123–4); Gebel Mukhezin, ½ km. towards Huseyin Village, Farsan Kebir.

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1908. ,, ,, ,, 5, i, 189.
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ADDENDUM.

By W. A. Macfadyen, M.C., Ph.D., F.G.S.

As the writer was abroad when the proofs of Part I were ready, a few slight additions and modifications are necessary.

On p. 311 (see Geological Magazine, 1930), it was stated that no igneous material was found in the Farsan Islands; this referred to the sedimentary series. There is a possibility that a few small islands south of Farsan Kebir and north of 16° N. Lat., namely, Berri (N.), Zumher, Baklan, Tokala, Dünje, Maflagein, Fasht, and Sana may consist mainly of basalt of the late Tertiary to Quaternary Aden Series. Owing to the political situation the writer was not able to land on these islands, but, sailing close past them, they appeared to be mainly of black basalt. On the other hand, black rocks said by natives to be similar were reported on Ferafer I. and Abu Shugar Islet, between Mandhar I. (E) and Gizan. These islands were visited, but the black rocks were found to be Reef Limestone, undercut in the usual way, and often completely blackened, simply as a result of marine erosion. Natives who had landed on the Baklan I. group were not sufficiently discriminating between basalt and blackened limestone for their opinion to be of value.

Since parts 1 and 2 of this paper were published, two papers dealing with aspects of the geology of the Farsan area have appeared:—

1931. Lees, G. M., "Salt. Some depositional and deformational problems." *J. Inst. Petrol. Tech.,* xvii, 259–80.
Wade, A. "Intrusive salt bodies in Coastal Asir, South Western Arabia." *Tome cit.,* 321–30.

p. 312. The scale of the map (Fig. 1) is incorrectly given; for 1 : 710,000 read 1 : 1,280,000 (approx.).

p. 314, 23rd line from top, should read: A boring on Zifaf Island passed through 120 metres of coral limestone, marly limestone and marls, with a little anhydrite and red shale near the base, which overlay rock salt to a depth of 473 metres.

p. 314, footnote. For *Euryptixis* read *Euryptyxis.*

REVIEWS.

THE PERMIAN OF MONGOLIA. By A. W. GRABAU. Natural History of Central Asia. Vol. IV. Central Asiatic Expeditions. American Mus. of Nat. Hist., N.Y. 1931. 10 dollars.

THIS is the second to appear of a series of twelve volumes describing the results of the Central Asian Expedition sent out by the American Museum of Natural History under the leadership of Dr. Roy Chapman Andrews. The fossils described in the present volume were collected in the years 1922, 1923, 1925, chiefly by Mr. Frederick K. Morris.

Almost the whole of this large volume is devoted to the Jisu Honguer formation of Mongolia, approximately half of the book being a detailed account of the fauna and the remainder a discussion of the formation and of its possible relations throughout Asia and Europe.

The Jisu Honguer area is a down-faulted block occupying, so far as is known, about 20 square miles in the heart of Mongolia.

The fauna comprises 4 species of Anthozoa, 99 species and varieties of Brachiopoda, 15 of Pelecypoda, and 18 of Gastropoda. All of these are excellently illustrated on thirty-five collotype plates. The fauna is discussed very fully, the known occurrences of each species being tabulated. For comparison with Jisu Honguer an account is given of the Permian and Upper Carboniferous rocks of Russia, including the Donetz Basin, India, the East Indies, China, and the Tethys Sea deposits. This section of about 150 pages is very useful as it summarizes the views of many writers and much literature. The purpose is, of course, to find the age of the Jisu Honguer formation.

The author holds that stratigraphical work is aided by the separation of distinct mutations of species under separate names, which no doubt is in accordance with modern ideas. A considerable number of the forms described, however, are represented by single specimens, and not uncommonly by one shell-valve only, and it seems possible that further collecting may modify a number of determinations. A query after a name might be used more frequently with advantage. Thus, the two species of *Schizodus* are both new and are represented by a single valve each and it is mentioned that as the teeth are not seen they may belong to *Protoschizodus*. The generic name chosen is the one more in accordance with the supposed age of the formation, Permian rather than Carboniferous. In this case the lack of a query weights the evidence unduly in favour of a Permian age. The occurrences of 84 of the 137 species and varieties are tabulated, but this rather exaggerates the Permian aspect of the fauna. Thus three forms in all are found to be present in the

Zechstein, but one of them, *Sireptorhynchus pelargonatus*, is represented by one valve only and is possibly a new variety, *Geinitzella columnaris* may also be a new variety, and *Dielasma elongata* var. *orientalis* is a new variety not known in the Zechstein but known in the Schwagerina Limestone (i.e. basal " Permian "). It appears therefore that the Jisu Honguer limestone has no Zechstein affinities. Other fossils from Jisu Honguer are closely related to Lower Carboniferous forms, e.g. *Pseudomonotis mongoliensis* and *P. furcoplicatus*, but such species are not found in the correlation tables. The effect of these matters is to give a newer appearance to the beds than would otherwise be the case.

The author concludes that the Jisu Honguer formation is approximately of the same age as the Schwagerina Beds of Russia and the Middle Productus Limestone of India. According to many geologists this would make them Carboniferous.

The correlation of the Schwagerina Beds with the Middle Productus Limestone is interesting since C. Schuchert (*Bull. Geol. Soc. Am.*, vol. 39, 1928) correlates the Schwagerina Beds with the lowest beds of the Rothliegende and the Middle Productus Limestone with the middle part of the Zechstein !

R. L. Sherlock.

CORRESPONDENCE.

SALT-PLUGS.

Sir,—Mr. J. V. Harrison's account of the salt-plugs of Southern Persia, published in the December number of the *Quarterly Journal*, 1930, is one of the most important contributions to physical geology which have recently appeared in Britain. Its exceptional interest naturally provokes a desire for further information. Has anyone measured the rate of flow of the Persian salt-glaciers by staking them out in the manner long ago adopted by students of ice-glaciers ? Has anyone experimentally investigated Mr. Harrison's convincing suggestion that certain of the salt-domes still play the part of slow-motion fountains feeding the salt-glaciers ? Mr. Harrison in reply to a question raised by Professor Watts has stated that there are two types of salt glaciers : the one with steep surface flows solidly as if made of glacier-ice ; the other with gently inclined surface is distributed by solution and recrystallization, so that its motion has some analogy to that of travertine or silicious sinter. Presumably these two types can readily be distinguished, for only the former should carry superficial erratics. Would it not be well to restrict the term salt-glacier to salt that has travelled in ice-glacier fashion ? When one speaks of erratics in connection with Persian salt, one naturally thinks of the Hormuz rocks, some of the sedimentary members of which carry Cambrian fossils. These salt-entangled